October 23, 2019

Marlene H. Dortch, Esq.
Secretary
Federal Communications Commission
445 12th Street SW
Washington DC 20554

Re: RM-11836, MB Docket No. 13-249

Dear Ms. Dortch:

The National Association of Broadcasters (NAB) supports the above-captioned Petition for Rulemaking filed by Bryan Broadcasting Corporation, which asked the Commission to initiate a proceeding to allow AM radio stations to voluntarily broadcast in the MA3 all-digital mode of HD radio.[1] We agree with Bryan that all-digital AM service will allow broadcasters to provide substantially improved sound quality.

In our comments on the Petition, we noted that NAB's broadcast technology innovation initiative PILOT, in cooperation with Xperi, transmitter manufacturers, AM radio stations and others, has conducted a series of field and laboratory tests of the HD Radio all-digital AM system, to develop a technical record of operation in this mode.[2] These experiments validated the successful performance of all-digital AM radio service. To supplement the record in this proceeding, NAB hereby submits three technical papers that describe the parameters and results of the tests referenced in NAB's comments.

Additionally, a paper from the 2019 NAB Broadcast Engineering and Information Technology Conference Proceedings offering technical information on the first full-time all-digital AM station, WWFD (Frederick, MD), owned by Hubbard Radio, is relevant to this proceeding. Please find that paper also attached.

---

[1] Petition for Rulemaking to Further AM Revitalization, Bryan Broadcasting Corp. (Bryan), RM-11836, MB Docket No. 13-249 (Mar. 25, 2019); Comments of NAB, RM-11836, MB Docket No. 13-249 (May 11, 2019).
[2] *See* https://nabpilot.org/work/projects/all-digital-am-radio-testing/.

We appreciate the opportunity to help inform the Commission's deliberations.

Respectfully submitted,

Larry Walke
Associate General Counsel
Legal and Regulatory Affairs
National Association of Broadcasters

cc: Al Shuldiner

# WBCN All-digital AM IBOC Field Test Project

David H. Layer
National Association of Broadcasters
Washington, DC

Alan Lane
CBS Radio
Charlotte, NC

Russ Mundschenk
iBiquity Digital Corporation
Columbia, MD

E. Glynn Walden
CBS Radio
Philadelphia, PA

Dennis Wallace
Meintel, Sgrignoli & Wallace
Waldorf, MD

Tom King
Kintronic Labs
Bluff City, TN

**Abstract** – *CBS Radio AM station WBCN, 1660 kHz, Charlotte, NC, obtained an experimental license from the FCC in late 2012 for operation in the iBiquity in-band/on-channel (IBOC) HD Radio all-digital MA3 mode. A project team consisting of NAB Labs, CBS Radio and iBiquity calibrated this all-digital transmission and then made daytime and nighttime digital coverage measurements for both indoor and outdoor reception. This paper describes the test procedures used and the preliminary results obtained from this field test project.*

## INTRODUCTION

The HD Radio in-band/on-channel (IBOC) digital radio system, developed by iBiquity Digital Corporation and standardized by the National Radio Systems Committee (NRSC) [1], can operate in two fundamental modes – hybrid and all-digital. The hybrid mode, which utilizes a radio signal consisting of the legacy analog signal (AM or FM), was authorized for use in the U.S. by the FCC in 2002, and at present over 2,200 radio stations are broadcasting a hybrid HD Radio signal.

iBiquity and others have contemplated that the transition to digital radio using the HD Radio system could encompass two phases: the introduction of digital radio services using the hybrid signal (spectrum shown in Figure 1), which would continue to allow for reception of the main channel audio portion of the signal on legacy analog receivers, and an eventual transition from the hybrid signal to the all-digital signal (spectrum shown in Figure 2), when there was sufficient penetration of HD Radio receivers in the marketplace so as not to disenfranchise listeners (on the order of 85% of listeners). Use of the all-digital signal would be advantageous because of its increased payload capacity and robustness, however, these advantages must be traded off against the loss of reception by analog receivers, which are numerous.

Unlike the hybrid AM IBOC system, the all-digital system has undergone very little testing (outside of that conducted by iBiquity when designing the system), and it has not been evaluated by the National Radio Systems Committee (NRSC).[1] The only publicly released test report by iBiquity on the all-digital AM IBOC system, from 2002 [4], documents field testing and "…highlights the improved performance that will be achieved by converting from the IBOC hybrid mode to all-digital broadcasting." [2]

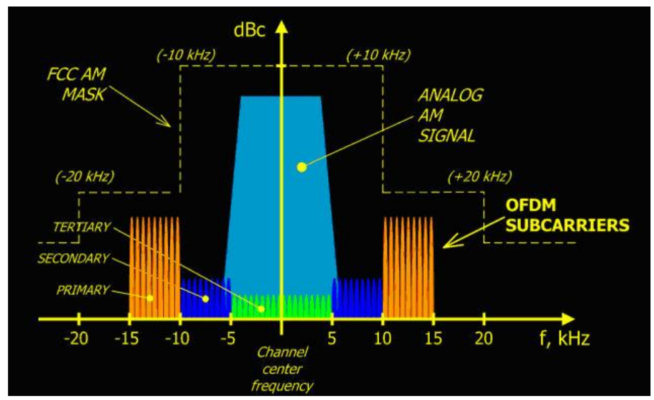



FIGURE 1. HYBRID AM IBOC SIGNAL SPECTRUM

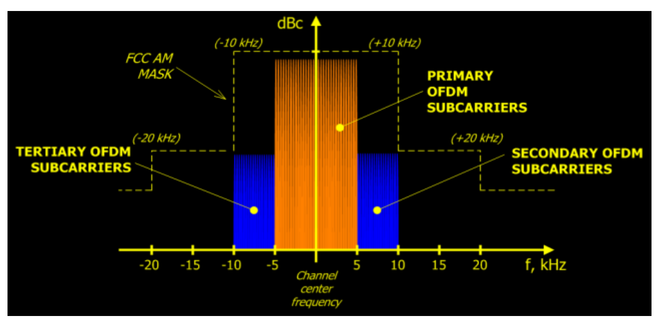



FIGURE 2. ALL-DIGITAL AM IBOC SIGNAL SPECTRUM

Currently (January 2013), with approximately 10 million HD Radio receivers deployed, there is no known effort on behalf of consumers or anyone in the broadcasting industry to advocate for a transition to all-digital HD Radio services, and in fact, all-digital broadcast radio transmissions are not currently allowed by the FCC except under experimental authorization. However, as the number of HD Radio receivers in use increases and even accelerates, it is

[1] iBiquity submitted a detailed test report on the hybrid AM IBOC system to the NRSC in January 2002 [2] which was evaluated by the NRSC's Digital Audio Broadcasting (DAB, now Digital Radio Broadcasting, DRB) Subcommittee [3].

[2] See [4] at page 2.

conceivable that at some point broadcasters will be interested in considering a transition to the all-digital mode of operation. This may be true more so for the AM-band version of HD Radio than the FM-band version, since the hybrid AM IBOC system has not been as widely accepted by the industry as has been the FM IBOC system.[3]

Deployment of all-digital IBOC services would require a change to the FCC rules, but to-date very little technical information on all-digital operation has been entered into the public record which is an impediment to FCC action in this regard.[4] In 2012, CBS Radio approached NAB Labs and iBiquity, offering to make AM station WBCN (1660 kHz, Charlotte, NC) available on a limited basis for all-digital AM IBOC testing, providing an opportunity to begin developing a contemporary test record that would help educate the industry as to the capabilities of all-digital operation, develop all-digital operational parameters, and provide information which could be eventually submitted to the FCC for the purposes of obtaining permanent authorization for all-digital service. The test plan and results described below were developed and obtained to take advantage of this limited opportunity.

### DESCRIPTION OF FACILITIES

WBCN is a 10 kW daytime, 1 kW nighttime non-directional facility that typically operates in HD Radio MA1 mode (hybrid AM IBOC); station information is given in Table 1. The antenna and transmitter building are shown in Figure 3.

WBCN's main transmitter is a Harris DX-10 fed by a Harris Dexstar exciter. Under normal operating conditions the DX-10 is used for both day and night operation, however, WBCN also has a 1 kW Nautel transmitter available as a backup. A photograph of the equipment room is shown in Figure 4.

### TEST PLAN

A relatively simple test plan was established for this project, reflecting the limited timeframe available for all-digital testing,[5] and designed to satisfy two principal goals:

1) Develop a procedure for establishing the correct (*i.e.*, licensed) transmit power for the all-digital AM IBOC signal, for both 10 kW (daytime) and 1 kW (nighttime) operation. This was necessary because industry standard procedures (and equipment) used for establishing AM

[3] For example, according to iBiquity, in 2011 there were 269 AM IBOC stations (out of 4,763 AM stations, approximately 6%) while there were 1,762 FM IBOC stations (out of 10,102, approximately 17%).

[4] FCC rules for digital radio are included in CFR 47 Section 73, Subpart C – Digital Audio Broadcasting.

[5] WBCN was made available for all-digital daytime testing for three weekends in late November and December 2012, and on a limited basis for all-digital nighttime testing during the same timeframe. At this time of year, approximately 10 hours were available each weekend day for testing (from 7AM to 5PM).

TABLE 1. WBCN STATION INFORMATION

| | |
|---|---|
| **Call sign** | WBCN |
| **Frequency** | 1660 kHz |
| **Station class** | B |
| **Community of license** | Charlotte, NC |
| **FCC Facility ID** | 87037 |
| **Digital status** | Hybrid |
| **Daytime power** | 10 kW |
| **Nighttime power** | 1 kW |
| **Location** | 35° 14' 56.00" N latitude 80° 51' 44.00" W longitude |
| **Configuration** | ND1 (non-directional antenna) |
| **Antenna** | Guyed, uniform cross section radiator, electrical height of 90.7° |

FIGURE 3. WBCN TRANSMISSION FACILITY SHOWING ANTENNA AND TRANSMITTER BUILDING. NOTE THE PRESENCE OF A 6" GRID DISH MOUNTED NEAR THE TOP OF THE TOWER WHICH IS USED FOR A 950 MHZ STL (AND ISOLATED FROM THE TOWER USING AN ISOCOUPLER).

radio station transmit power rely upon the presence of an analog AM signal which, of course, is not present in an all-digital transmission. Described in the sections below is a procedure developed under this test project to establish a 10 kW and 1 kW all-digital MA3 mode AM IBOC transmission. As part of this power calibration procedure, attention was also paid to optimization of the all-digital AM IBOC exciter parameters so as to achieve good compliance with the RF mask for MA3 mode operation that is included in the NRSC-5 Standard.[6]

[6] See [1], Normative Reference [8] (iBiquity reference document 1082s, rev. F), Table 4-4 and Figure 4-4.

FIGURE 4. WBCN TRANSMISSION EQUIPMENT – FROM LEFT TO RIGHT, NAUTEL 1 KW BACKUP TRANSMITTER (AT VERY EDGE OF PHOTO), HARRIS DX-10 10 KW TRANSMITTER, RACK WITH RF SWITCH, RACK WITH HARRIS DEXSTAR EXCITER, AUDIO PROCESSORS, AND STL EQUIPMENT.

2) Characterize the reception coverage of the all-digital AM IBOC signal for both mobile (in-vehicle) reception as well as for indoor reception. For the mobile testing, eight test routes were defined, each starting at the transmitter location and proceeding away from the transmitter, in directions corresponding roughly to the eight cardinal directions of N, NE, E, SE, S, SW, W, and NW. Under the test plan, a test vehicle was to be driven along each route to determine the point-of-failure (POF) of the all-digital AM IBOC signal, for both daytime and nighttime reception conditions, with POF being the point at which reliable reception of the all-digital signal was lost.[7] As part of this process, reception information including vehicle speed and location and received signal strength were to be recorded.

For indoor testing, the test plan called for going to a variety of locations dispersed throughout the station's coverage area and assessing the indoor reception quality of the all-digital AM IBOC signal using an Insignia Narrator tabletop radio, for a variety of building types. Signal strength readings were collected for these indoor measurements, as well, using a Scott LP-3 shielded loop antenna connected to a Rhode & Schwarz spectrum analyzer.

Of significant interest was the audio quality of WBCN's AM analog signal at the locations where the all-digital AM IBOC signal fails. To establish this for the mobile tests, the geographic coordinates of the digital POF were recorded, then when the WBCN transmitter was re-configured for analog transmission (usually on the subsequent day or night), these coordinates were re-visited and an audio recording of the analog signal was made. For the indoor tests, audio recordings and signal strength measurements were obtained under four test conditions at each indoor location: analog daytime and nighttime, and digital daytime and nighttime.

### WBCN'S ANTENNA SYSTEM

The WBCN antenna utilizes a guyed, series fed, 24-inch facewidth, triangular tower having an electrical height of 90.7 electrical degrees(45.5m). The antenna system was designed for AM HD Radio hybrid IBOC operation taking into consideration the -45° phase shift of the output network of the Harris Model DX-10 transmitter, 17 feet of Myat 1-5/8" rigid line between the transmitter output and the RF switch, 150 feet of Andrew Type LDF7-50A 1-5/8" foam heliax between the RF switch and the antenna tuning unit (ATU), the phase shift of the Kintronic Labs ATU and the measured drive impedance of the tower while taking into consideration the effects of the LBA STL isocoupler across the base of the tower. A diagram of the complete transmission system with the associated phase shifts for each component as output from the Kintronic Labs CKTNET program is shown in Figure 5.

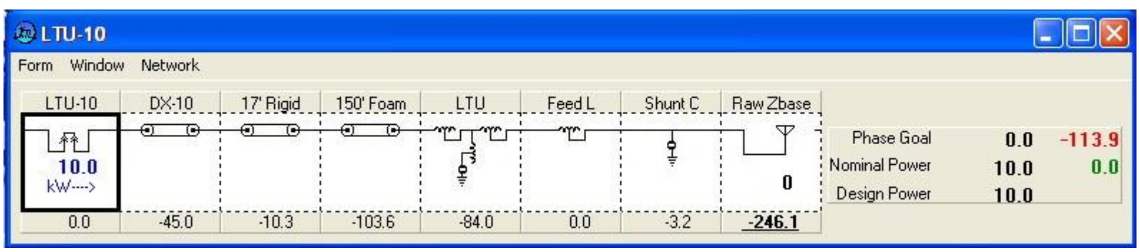
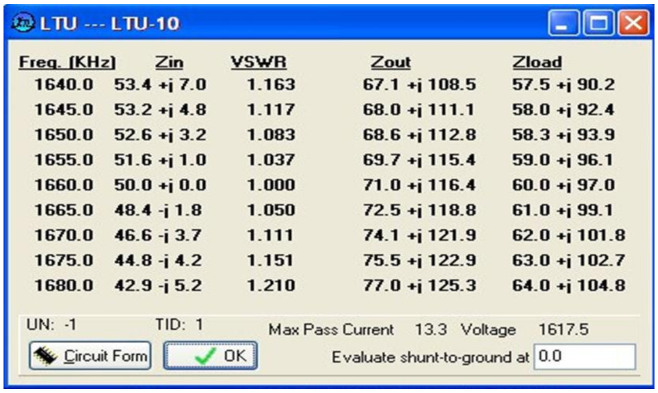



FIGURE 5. CKTNET DESCRIPTION OF THE WBCN TRANSMISSION SYSTEM SHOWING THE ASSOCIATED PHASE SHIFTS FOR EACH COMPONENT. NOTE THAT THE ATU IS DESIGNATED "LTU" (WHICH IS AN ACRONYM FOR "LINE TERMINATING UNIT").

The components denoted as "Shunt C" and "Feed L" in Figure 5 represent the shunt capacitance presented by the STL isocoupler and the series inductance presented by the RF buss between the ATU output and the tower, respectively. The measured drive impedance of the tower, not including the effects of the isocoupler or the RF buss, is shown as Zload in Figure 6. Note that the impedance seen by the ATU is shown as Zout in this figure.

The goal of the ATU design was to yield Hermitian symmetry at the combined final RF amplifier output of the Harris DX-10 transmitter with a VSWR of less than 1.4:1 at the +/-20 kHz sidebands based on the load impedance presented at the output bowl of the ATU, which is shown as Zout in Figure 6. The Zin and VSWR shown in Figure 6 are the carrier and sideband impedance and VSWR at the input

[7] Unlike the hybrid AM IBOC signal, which "blends" to the analog signal at the point of digital failure, when the all-digital AM IBOC signal fails the receiver simply mutes.



LTU --- LTU-10

| Freq. (KHz) | Zin | VSWR | Zout | Zload |
|---|---|---|---|---|
| 1640.0 | 53.4 +j 7.0 | 1.163 | 67.1 +j 108.5 | 57.5 +j 90.2 |
| 1645.0 | 53.2 +j 4.8 | 1.117 | 68.0 +j 111.1 | 58.0 +j 92.4 |
| 1650.0 | 52.6 +j 3.2 | 1.083 | 68.6 +j 112.8 | 58.3 +j 93.9 |
| 1655.0 | 51.6 +j 1.0 | 1.037 | 69.7 +j 115.4 | 59.0 +j 96.1 |
| 1660.0 | 50.0 +j 0.0 | 1.000 | 71.0 +j 116.4 | 60.0 +j 97.0 |
| 1665.0 | 48.4 -j 1.8 | 1.050 | 72.5 +j 118.8 | 61.0 +j 99.1 |
| 1670.0 | 46.6 -j 3.7 | 1.111 | 74.1 +j 121.9 | 62.0 +j 101.8 |
| 1675.0 | 44.8 -j 4.2 | 1.151 | 75.5 +j 122.9 | 63.0 +j 102.7 |
| 1680.0 | 42.9 -j 5.2 | 1.210 | 77.0 +j 125.3 | 64.0 +j 104.8 |

UN: -1 TID: 1 Max Pass Current 13.3 Voltage 1617.5

Circuit Form OK Evaluate shunt-to-ground at 0.0

FIGURE 6. WBCN MEASURED TOWER DRIVE IMPEDANCE. NOTE THAT ZLOAD DOES NOT INCLUDE THE EFFECTS OF THE ISOCOUPLER OR THE RF BUSS FROM THE ATU TO THE TOWER.

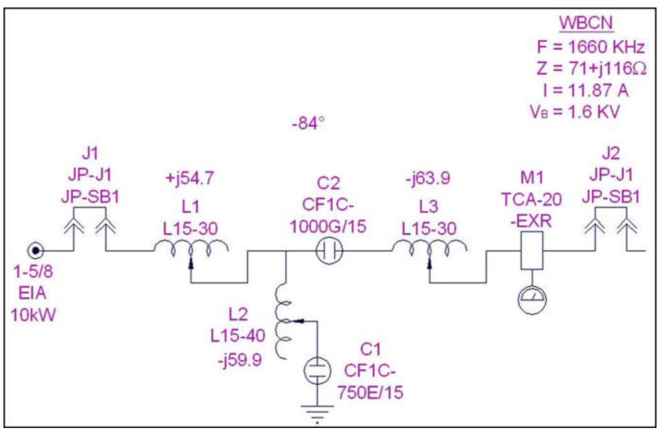



FIGURE 7. SCHEMATIC FOR THE WBCN ANTENNA TUNING UNIT (ATU).

j-plug of the ATU. The optimized ATU design is shown in Figure 7.

Figure 8 shows a Smith chart of the final impedance locus that was presented to the final combined amplifier output of the Harris DX-10 transmitter, which yields the desired +/-20 kHz sideband VSWR of < 1.4:1 with Hermitian symmetry that is required for HD Radio hybrid AM IBOC mask-compliant operation. The dashed circle represents a VSWR of 1.4:1.

Note that in general, an AM antenna that is optimized for HD Radio hybrid AM IBOC (such as the one at WBCN) is also optimized for all-digital AM IBOC, given that the all-digital signal bandwidth is actually less (+/- 10 kHz) than that of the hybrid signal (+/- 15 kHz), as shown above in Figure 1 and Figure 2.

### TRANSMITTER CALIBRATION

As discussed above, it was necessary under this project to develop a procedure for setting the correct all-digital AM IBOC transmitter RF output level. Due to the limited peak capability of the DX-10 transmitter, an adjustment of power

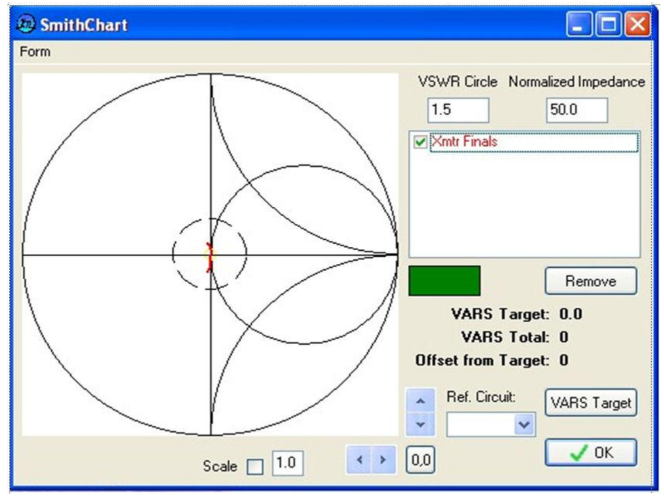



FIGURE 8. SMITH CHART OF NORMALIZED IMPEDANCE PRESENT AT THE FINAL COMBINED RF AMPLIFIER OUTPUT OF THE DX-10 TRANSMITTER.

output was necessary to maintain maximum peak-to-average ratio (PAR) while avoiding clipping of the modulation peaks. Clipping results in excessive intermodulation distortion (IMD) products and potential non-compliance with the iBiquity MA3 mask.

Prior to determining the proper RF output operating point for the system, the base impedance of the tower was verified as 71 +j116 ohms at the carrier frequency. A Delta Electronics TCA-20 ammeter was used as the reference to determine actual power output.

In order to enable the all-digital AM mode (MA3), Harris supplied updated Dexstar software, IRSS version 4.4.7 (this was "pre-release" software developed especially for this project). The DX-10 transmitter was used for essentially all analog and digital testing modes to obtain the data for this project. A backup Nautel 1 kW transmitter, fed directly by an Orban Optimod audio processor, was used in some instances to provide the 1 kW analog signal. Setting the proper RF output to achieve maximum RMS power and MA3 mask compliance is described below.

The RF power measurement was obtained by first setting the reference level for the RF spectrum analyzer (an Agilent E4402B). The DX-10 transmitter was set to the HIGH power level and the Dexstar exciter was placed in the "AM ALL DIGITAL" mode, then in CW analog AM mode by turning the digital carrier off (see Dexstar user interface shown in Figure 9). The transmitter was adjusted as necessary for an indication of 10 kW forward power on the transmitter output power meter. An antenna base current of 11.8 A was observed (Figure 10). This verified the accuracy of the transmitter's RF output power meter.

The spectrum analyzer was connected through a 30 dB pad to the transmitter's output monitor board which, at the HIGH power setting, provides an adjustable sample using an on-board rheostat. The spectrum analyzer was set to the carrier frequency with 10 kHz resolution bandwidth, RMS

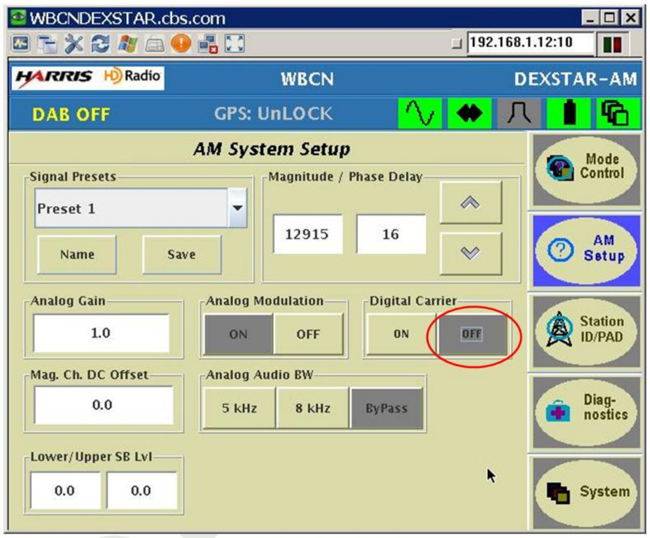



FIGURE 9. DEXSTAR GRAPHICAL USER INTERFACE (GUI) IN CW AM MODE

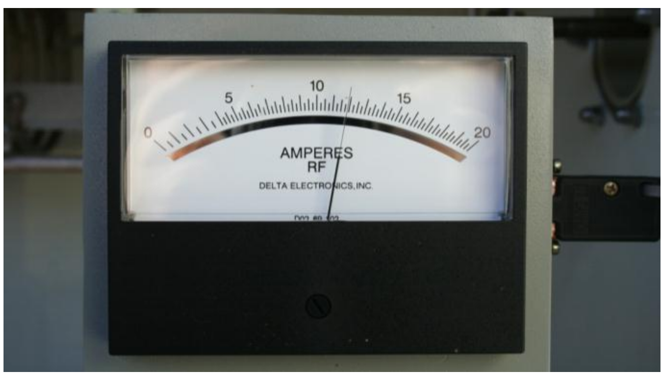



FIGURE 10. BASE CURRENT AMMETER IN AM CW MODE

power averaging, detector mode to Sample, and averaging turned on (10 averages). The output monitor board was then adjusted to produce a 0 dBm reference level on the spectrum analyzer (Figure 11).

A Rohde & Schwartz NRP-Z92 average power sensor was further used to calibrate transmitter output power. Once the spectrum analyzer reference was determined, the transmitter RF sample was connected directly to the power sensor. The NRP Toolkit PC software used with the power sensor was launched and the sensor was connected to the PC via USB interface. The carrier frequency and offset value were adjusted in the PC software to indicate 10 kW power (Figure 12). An offset value of 40.2 dB was used.

Next, the digital carrier was set to ON in the Dexstar exciter. The DX-10 transmitter power output was adjusted with the front panel RAISE and LOWER controls to indicate 10 kW average power on the power sensor software display. This resulted in an indication of 7.8 kW forward power on the transmitter output power meter (Figure 13). Approximately 51 A of PA current was noted (Figure 14).

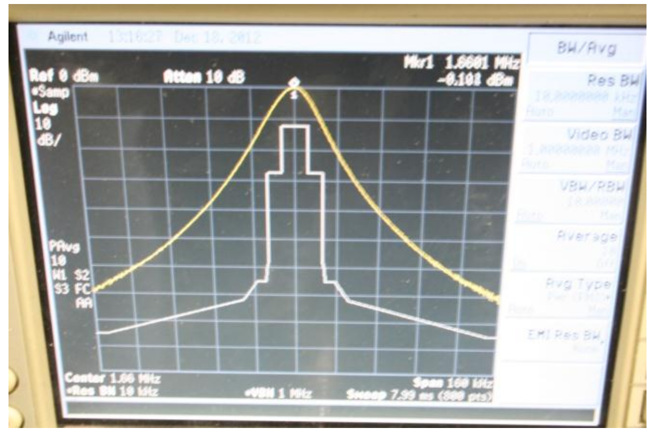



FIGURE 11. SPECTRUM ANALYZER REFERENCE LEVEL


FIGURE 12. POWER SENSOR CALIBRATION IN AM CW MODE

Finally, the RF sample was connected to the spectrum analyzer. Again, 30 dB of attenuation at the analyzer input was used. The analyzer settings were changed to a resolution bandwidth of 300 Hz and 100 averages. The NRSC-5-C MA3 mask limit file was loaded into the analyzer.[8] The I/Q Scale Factor and Magnitude/Phase Delay were adjusted with the Dexstar GUI in small increments while observing the spectrum analyzer so as to achieve maximum mask compliance.

The final output spectrum resulting from this procedure vs. the MA3 mask is shown in Figure 15. The settings obtained were used for all digital daytime measurements. The I/Q Scale Factor was 8000 and the Magnitude/Phase Delay was 12915 (Figure 16). Note that it was not possible to bring the spectrum entirely within the MA3 mode mask. This may be because this mask is in some sense "theoretical" and does not take into consideration what may be realizable with real-world transmission equipment. One of the likely consequences of this (and future) all-digital AM IBOC test projects is that this mask may be modified to

[8] See footnote 6.

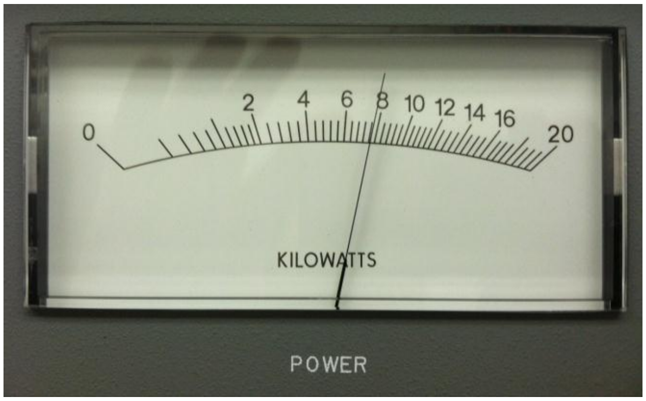



FIGURE 13. TRANSMITTER FORWARD POWER AT 10 KW IN MA3 MODE

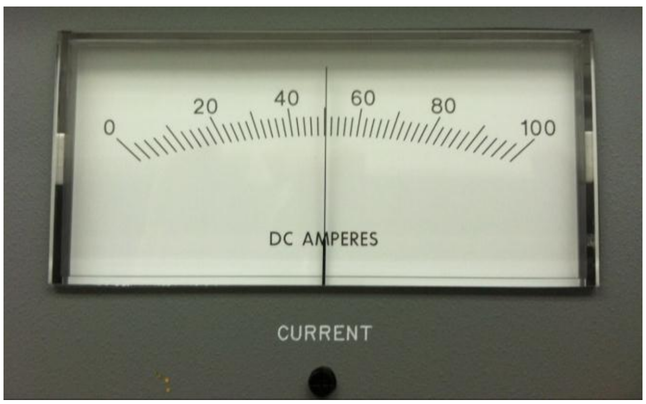



FIGURE 14. TRANSMITTER PA CURRENT AT 10 KW IN MA3 MODE

reflect real-world implementations, as has been the case for other IBOC implementation modes (for example, the hybrid FM IBOC mask was modified in a similar fashion after sufficient field experience with the hybrid FM IBOC system had been obtained – see [5]).

The 1 kW (nighttime) power level was set in the same manner with the following exceptions. The DX-10 transmitter has no easily adjustable RF sample output for the LOW power level. This required an adjustment in reference level and reference offset to be entered in the spectrum analyzer. Power calibration was achieved with the same procedure using the 1 kW base current value as reference. The DX-10 output power achieved was 800 watts for 1 kW average power in MA3 mode. Approximately 9 A of PA current was noted. The Dexstar I/Q Scale Factor was 7800 and Magnitude/Phase Delay was 12935. Figure 17 shows the spectrum in MA3 mode at 1 kW. A summary of the transmitter operational parameters for each mode is provided in Table 2 and Table 3.

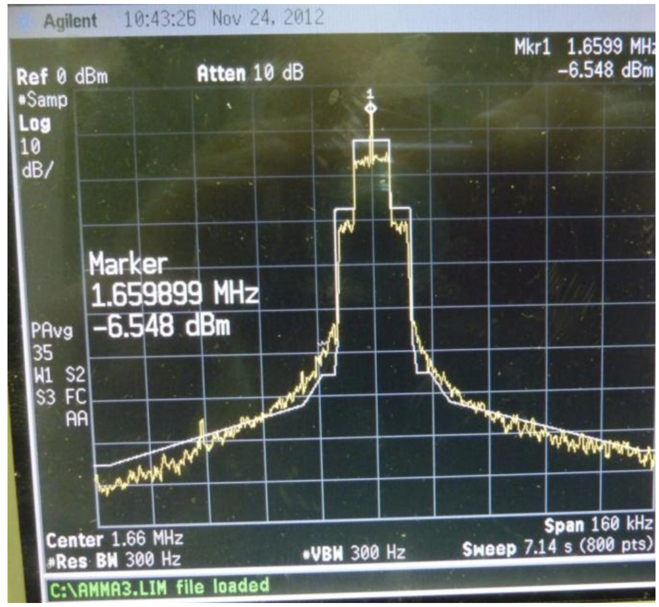



FIGURE 15. OUTPUT SPECTRUM AT 10 KW IN MA3 MODE


FIGURE 16. DEXSTAR FINAL SETTINGS FOR 10 KW MA3 MODE

### TEST RESULTS – MOBILE TESTING

Once the transmitter was properly calibrated for operation in MA3 mode, an iBiquity test vehicle was driven along each test route to establish the digital POF (Figure 18). A block diagram of the equipment in the test vehicle is shown in Figure 19 and is described here:

- Principal determination of all-digital signal reception and POF was done using an OEM Ford Sync HD Radio receiver that was factory-installed in a Ford Focus



PREVIOUS VIEW

TABLE 2. SUMMARY OF TRANSMISSION PARAMETERS - DAYTIME

| Parameter | Analog | Digital (MA3) |
|---|---|---|
| Forward power as indicated on DX-10 (kW) | 10.0 | 7.81 |
| PA current as indicated on DX-10 (A) | 54 | 51 |
| Antenna base current (A) | 11.8 (carrier only) | 10.6 |
| Dexstar I/Q scale factor | n/a | 8000 |
| Dexstar mag / phase delay | n/a | 12915 |

TABLE 3. SUMMARY OF TRANSMISSION PARAMETERS - NIGHTTIME

| Parameter | Analog | Digital (MA3) |
|---|---|---|
| Forward power as indicated on DX-10 (kW) | 1.0 | 0.8 |
| PA current as indicated on DX-10 (A) | 9 | 9 |
| Antenna base current (A) | 3.75 | 3.4 |
| Dexstar I/Q scale factor | n/a | 7800 |
| Dexstar mag / phase delay | n/a | 12935 |

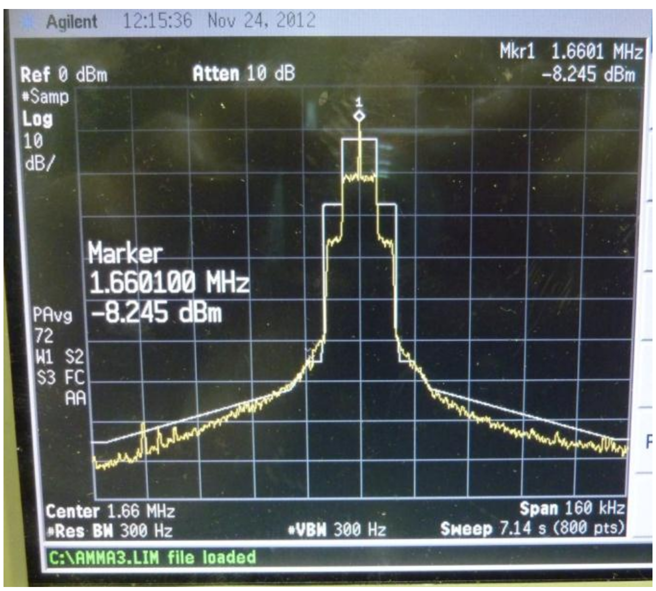



FIGURE 17. OUTPUT SPECTRUM AT 1 KW IN MA3 MODE

automobile and connected to the vehicle's built-in antenna. A custom data interface to this receiver was designed by iBiquity utilizing the auto's "I2C" data bus allowing for connection to a laptop computer ("Laptop #1 in Figure 19). Note that principal determination of all-digital signal reception was done using this receiver/antenna combination since this most accurately represents an actual consumer experience;

FIGURE 18. IBIQUITY TEST VEHICLE SHOWING MILLIMETRICA ANTENNA INSTALLED ON THE ROOF.

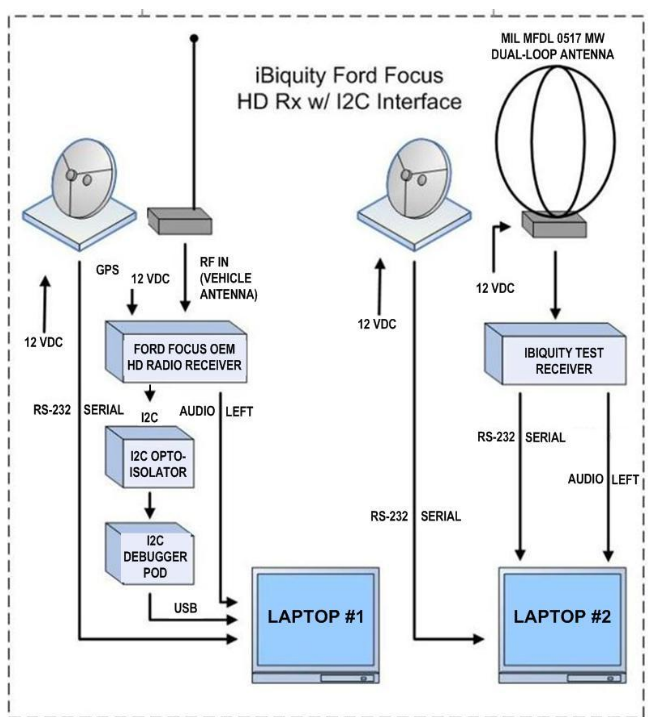



FIGURE 19. MOBILE TEST VEHICLE SETUP.

- Information collected on Laptop #1 was obtained from the OEM receiver as well as a GPS receiver (connected via USB) and included time (UTC), position (latitude and longitude), vehicle speed, receive mode (all-digital enhanced, all-digital core, no reception), and signal-to-noise ratio (SNR). The data collection software was custom-designed by iBiquity for AM HD Radio data collection;
- Laptop #2 collected similar information from an iBiquity test receiver located in the rear seat of the

Focus, and ran the same iBiquity custom-designed software as did laptop #1. This receiver was connected to a roof-mounted Millimetrica active dual-loop antenna and was able to provide more precise field strength measurements than the OEM receiver (connected to laptop #1). [6]

The typical experience on each test route was that all-digital reception would be solid, with no "drop-outs," in strong signal areas near the transmit antenna, and it would stay solid with only an occasional drop out until near the all-digital POF, at which point reception would fairly abruptly become intermittent and then be lost completely. Reception data collected from the Ford Sync receiver is illustrated below in Figure 20 for daytime reception and Figure 21 for nighttime reception. Some specific observations on the data in these figures:

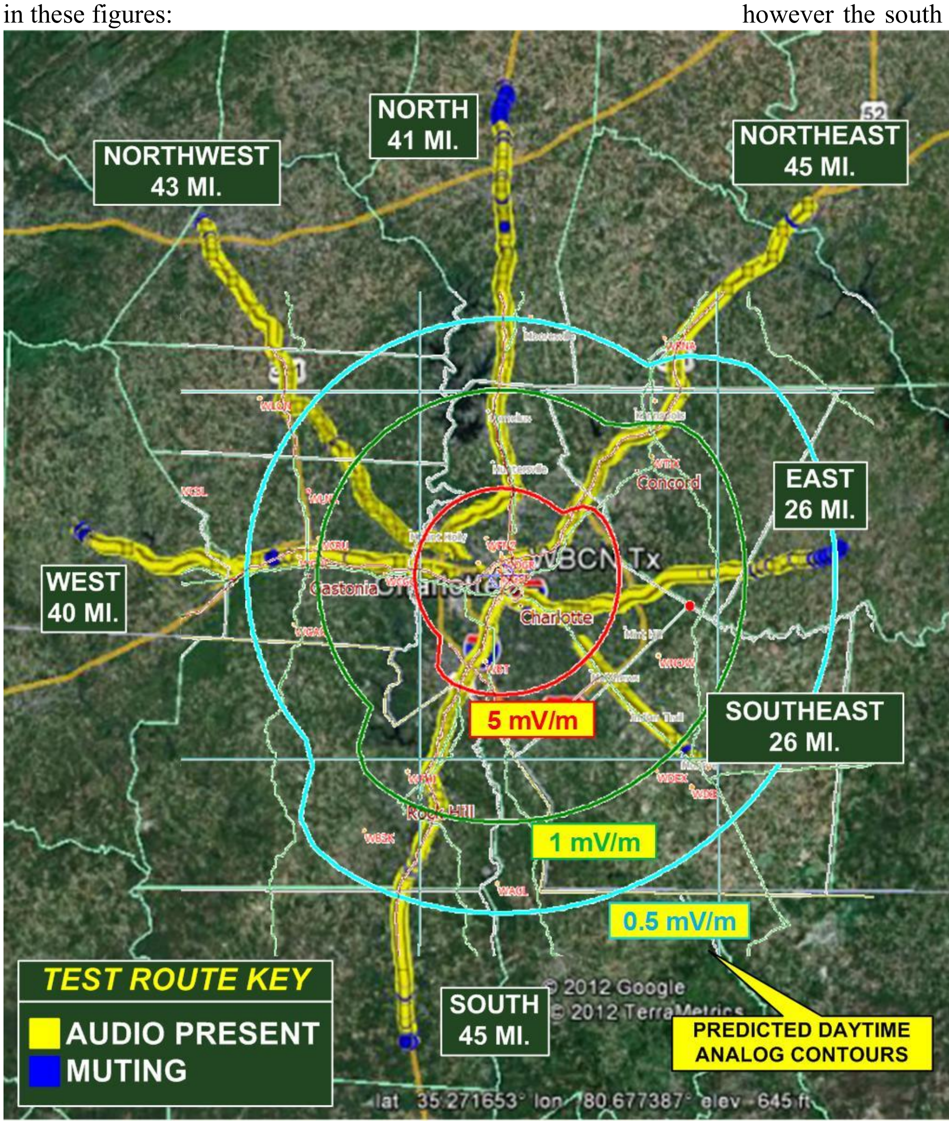



FIGURE 20. ALL-DIGITAL AM IBOC MOBILE TEST RESULTS – DAYTIME. FIGURES FOR EACH ROUTE INDICATE APPROXIMATE DISTANCE FROM TRANSMITTER TO ALL-DIGITAL AM IBOC POINT-OF-FAILURE (POF). OVERLAID ON THE ROUTE MAP ARE PREDICTED DAYTIME ANALOG AM CONTOURS FOR 5, 1, AND 0.5 MV/M.

- Predicted analog signal contours for WBCN are overlaid onto the all-digital mobile test route data, illustrating that for daytime operation, the all-digital signal was solid beyond the 1 mV/m contour, and for nighttime, beyond the 5 mV/m contour;
- Only seven of the eight planned test routes were driven for the daytime tests (no data on the southwest route was obtained). This is because there was just enough time during the first weekend of testing to collect data on the seven routes driven, and this data was deemed adequate for achieving the goals of the test. It was decided to go ahead and return the test vehicle to iBiquity's headquarters in Columbia, MD rather than keep it in Charlotte for an entire week to just do a single test run;
- For nighttime testing, all eight test routes were driven, however the south and southwest routes were the same for the first few miles and since the all-digital POF was encountered on the common part of these two routes, only the south route is shown in Figure 21. Also, portions of Interstate 485 were captured at night as well and are shown in the figure;
- Performance to the east and southeast was noticeably poorer than on the other routes. This is believed to be due in part to a greater amount of environmental noise, especially due to power lines in close proximity to the test routes;
- Surprisingly, nighttime performance appeared to be compromised by the presence of co-channel interference, which was not expected on an expanded-band AM station. It is believed that this was due to a nearby co-channel station may not have been fully powering down for nighttime operation.

After establishing the geographic coordinates for the all-digital POF for each test route, WBCN was configured for analog AM (not hybrid AM IBOC) transmission, and a second Ford Focus, this one with a factory-installed, non-HD Radio receiver (*i.e.*, analog only) was driven to each POF location. A recording of the analog receiver audio was made at each POF location with the vehicle parked on the side of the road using a Tascam DR-2d digital audio recorder [7], and signal strength measurements were made

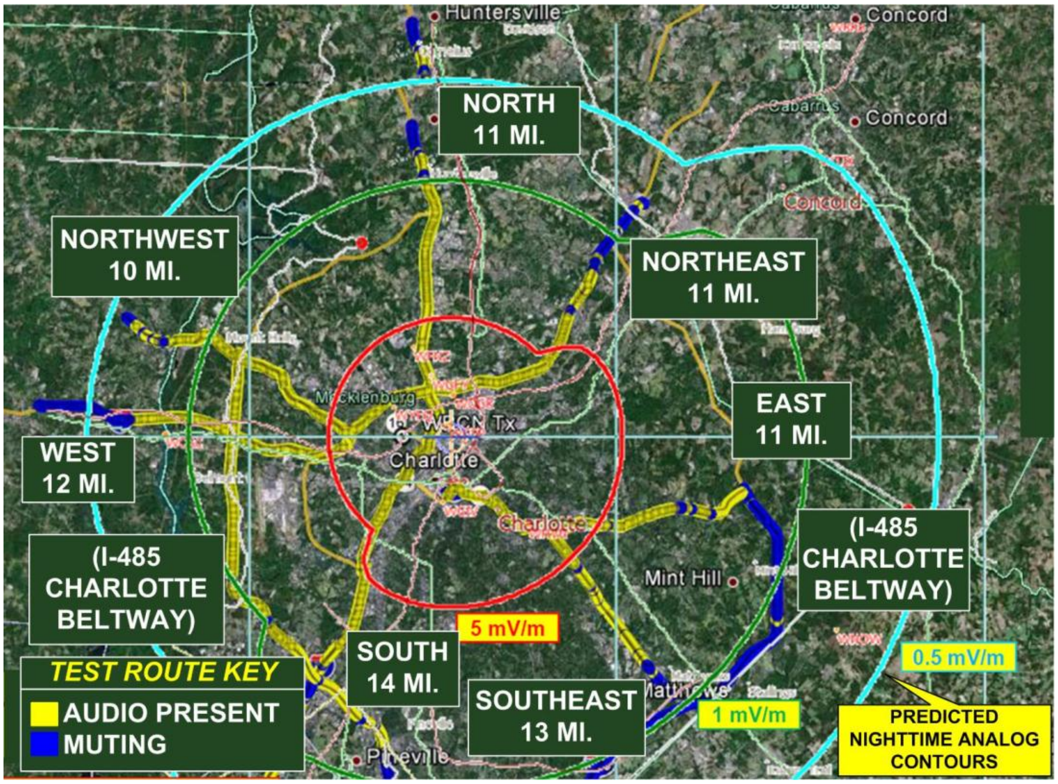



FIGURE 21. ALL-DIGITAL AM IBOC MOBILE TEST RESULTS – NIGHTTIME. FIGURES FOR EACH ROUTE INDICATE APPROXIMATE DISTANCE FROM TRANSMITTER TO ALL-DIGITAL AM IBOC POINT-OF-FAILURE (POF). OVERLAID ON THE ROUTE MAP ARE PREDICTED NIGHTTIME ANALOG AM CONTOURS FOR 5, 1, AND 0.5 MV/M.

using a Scott LP-3 shielded loop antenna connected to a Rhode & Schwarz spectrum analyzer (same equipment used for indoor signal strength measurements). [8] These recording and the signal strength data are currently under analysis and will be described in a future report.

### TEST RESULTS – INDOOR TESTING

Indoor reception tests were conducted at fifteen sites within the WBCN coverage area (Figure 22 and Figure 23), under four reception conditions: analog day, analog night, digital day, and digital night. An Insignia Narrator tabletop HD Radio receiver was used for these tests. [9] The Narrator receiver utilizes an AM loop antenna (included with the receiver), and at each site the position of this antenna was adjusted for best reception. The particular receiver and antenna orientation for each site was photographed and this photograph was used to ensure the same orientation for each of the four test conditions at that site. This was necessary since for most sites, four separate visits over the course of a few days were needed to obtain data under all four test conditions.[9]

Also, at each test site, for each reception condition, a signal strength measurement was made using a Scott LP-3 shielded loop antenna connected to a Rhode & Schwarz spectrum analyzer. Figure 24 is a photograph of a typical indoor measurement which was taken at site P, the lobby of a Fairfield Inn and Suites. Once the receiver's antenna was oriented for best reception, if reception was achieved then a two-minute audio recording was made for each site under each test condition by connecting a digital audio recorder (Tascam DR-2d) to the headphone jack of the Narrator receiver.

These indoor sites were representative of a variety of building construction materials including (letters refer to test sites shown in Figure 22 and Figure 23) steel (N, O, P), steel and masonry (B,Q), brick (D, C, F, E, K), and wood with siding or brick (G, H, I, L, M). Table 4 provides a summary of the results of these indoor tests. Some specific observations on the indoor test results include the following:

- Solid all-digital indoor reception was achieved for daytime and nightime locations within approximately 13 and 7 miles, respectively, of the transmit antenna site. As expected, these distances are significantly less than for mobile reception, where solid all-digital reception was achieved out to about 40 miles (daytime) and 11 miles (nighttime);
- One exception to this was the indoor reception experienced at site "C," the CBS Radio Epicentre Studio. Despite close proximity to the transmit site (1.97 mi), analog reception was poor (daytime) or non-existent (nighttime) yet good all-digital reception (daytime) was achieved. All-digital nighttime reception was attempted at this site but not achieved;
- For the last five sites in the table (H, I, Q, L, M) no actual digital nighttime reception was attempted since analog daytime reception was poor and analog nighttime reception was non-existent. This poor performance was attributed to the fact that all of these test sites are relatively far away (16 miles or more) from the transmit site.

[9] Note that for some sites, analog and digital night measurements were made in a single visit to the site, by remotely switching between the Harris DX-10 (set up for all-digital transmission) and the Nautel backup transmitter (set up for analog transmission).

PREVIOUS VIEW

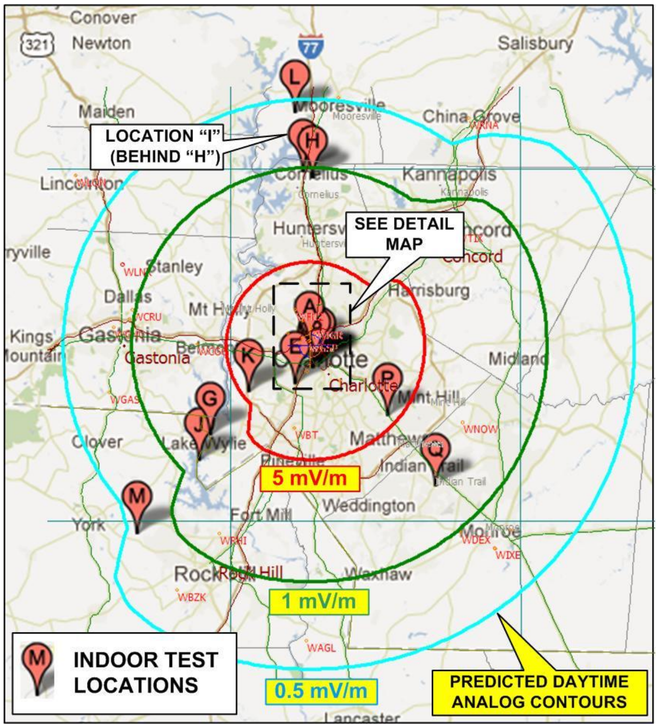



FIGURE 22. INDOOR TEST LOCATIONS ("A" IS THE WBCN TRANSMISSION SITE)

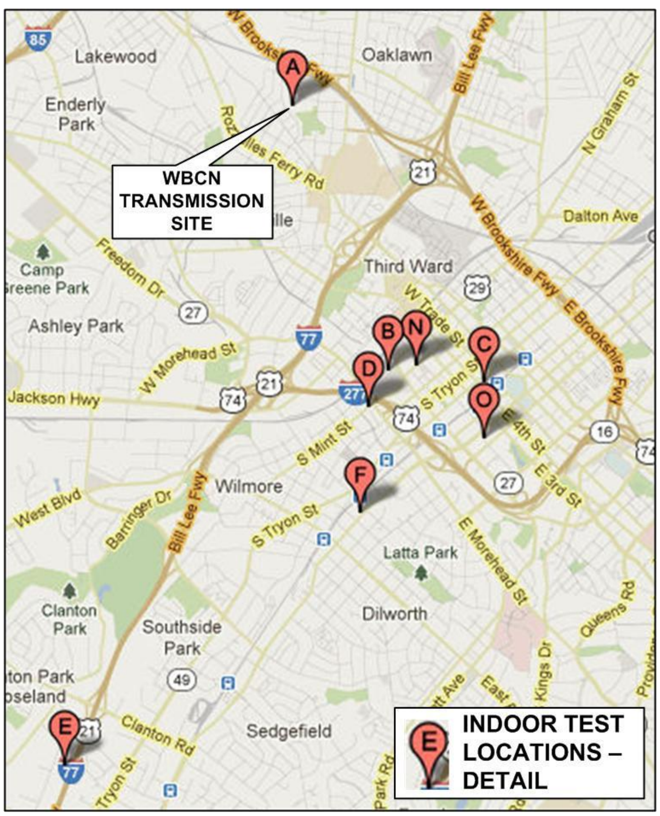



FIGURE 23. INDOOR TEST LOCATIONS – DETAIL

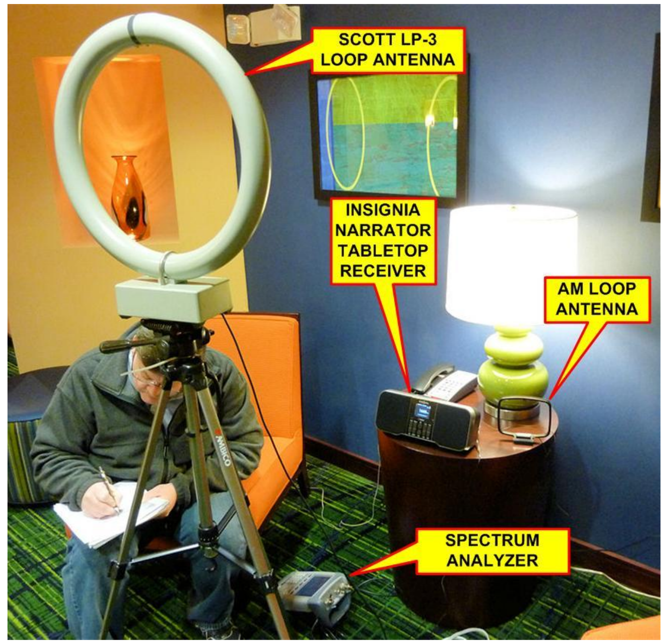



FIGURE 24. INDOOR MEASUREMENT EQUIPMENT SETUP AT SITE P (FAIRFIELD INN & SUITES). NOTICE THAT THE SCOTT AND INSIGNIA NARRATOR LOOP ANTENNAS ARE ORIENTED IN THE SAME DIRECTION; THIS WAS TYPICAL OF ALL MEASUREMENT SITES.

TABLE 4. INDOOR TEST LOCATION RECEPTION RESULTS

KEY: AD – Analog Day, AN – Analog Night, DD – Digital Day, DN – Digital Night

Analog reception: G – Good, F – Fair, P – Poor, n/a – not available

Digital reception: Green – Yes, Red – No, Yellow - Intermittent

| Map Key | Distance to TX antenna (mi) | Description | AD | AN | DD | DN |
|---|---|---|---|---|---|---|
| B | 1.66 | Bank of America Stadium | G | G/F | Green | Green |
| N | 1.69 | Residence Inn by Marriott | G | G/F | Green | Green |
| D | 1.83 | CBS Radio - "Doghouse" | G | G | Green | Green |
| C | 1.97 | CBS Radio - Epicentre studio | P | n/a | Green | Red |
| O | 2.25 | Hilton Garden Inn | G/F | F/P | Green | Green |
| F | 2.42 | CBS Radio studios | F | F/P | Green | Green |
| E | 4.10 | CBS Radio former studios | G/F | F/P | Green | Green |
| K | 7.60 | Fred Smith residence | G | F | Green | Green |
| P | 10.40 | Fairfield Inn & Suites | P | P | Green | Red |
| G | 13.03 | John Dolive residence | F | P | Green | Red |
| H | 16.01 | Hair Salon | P | n/a | Red | |
| I | 16.62 | Alan Lane residence | P | n/a | Yellow | |
| Q | 18.48 | McDonald's | P | n/a | Red | |
| L | 22.45 | Joshua Pierce residence | P | n/a | Red | |
| M | 24.95 | Brad Humphries residence | F/P | n/a | Green | |

*No service expected*

## SUMMARY AND FUTURE ACTIVITIES

This field test project, facilitated by CBS Radio's decision to allow for limited all-digital AM IBOC testing at WBCN in Charlotte, has resulted in the collection of important information pertaining to the operation of an AM IBOC radio station in the MA3 all-digital mode. Specifically, a procedure was developed for calibration of the transmitter power (in all-digital mode) to the licensed daytime and nighttime power of the station, and mobile and indoor all-digital AM IBOC reception data were obtained.

The project team is continuing to analyze the field strength measurements and audio recordings obtained during these tests, and expects to make this information available to the industry when this analysis is completed. NAB Labs expects to support future all-digital AM IBOC test projects at other stations so as to fully develop a performance record of operation in this mode.

## ACKNOWLEDGMENTS

The authors would like to thank the following individuals for their efforts and support: Bill Schoening (CBS Radio), Geoff Mendenhall and Terry Cockerill (Harris Broadcast), Jeff Detweiler and Mike Raide (iBiquity), and Kevin Gage and John Marino (NAB).

## REFERENCES

[1] NRSC-5-C, In-band/on-channel Digital Radio Broadcasting Standard, National Radio Systems Committee, September, 2011

[2] AM IBOC DAB Laboratory and Field Testing: Third Report to the National Radio Systems Committee, iBiquity Digital Corporation, January 4, 2002

[3] Evaluation of the iBiquity Digital Corporation IBOC System - Part 2- AM IBOC, National Radio Systems Committee, April 6, 2002

[4] AM All-digital IBOC Field Test Report, iBiquity Digital Corporation, April 12, 2002

[5] The HD Radio FM hybrid digital emission mask change was first submitted to the FCC by iBiquity in an Ex Parte filing dated July 5, 2006, in the digital radio proceeding (RM 99-325).

[6] Millimetrica website, www.millimetrica.it

[7] Tascam website, http://tascam.com/product/dr-2d/

[8] The Scott LP-3 is an antenna designed specifically for medium-wave signal measurements. Additional information may be found on this website: www.scott-inc.com/html/lp3.htm

[9] Insignia Narrator website, www.insigniaproducts.com/products/portable-audio-players/NS-CLHD01.html

## AUTHOR INFORMATION

**David H. Layer,** Senior Director, Advanced Engineering, National Association of Broadcasters, 1771 N Street, N.W., Washington, DC 20036

**Alan Lane,** Market Engineer/IT Manager, CBS Radio, 1520 South Blvd., Suite 300, Charlotte, NC 20203

**Russ Mundschenk,** Field Test and Implementation Manager, iBiquity Digital Corporation, 6711 Columbia Gateway Drive, Suite 500, Columbia, MD 21046

**E. Glynn Walden,** Senior Vice President Engineering, CBS Radio, 400 Market Street, 10th floor, Philadelphia, PA 19106

**Dennis Wallace,** Meintel, Sgrignoli & Wallace, 1282 Smallwood Drive West, Suite 372, Waldorf, MD 20603

**Tom King,** President, Kintronic Labs, Inc., 144 Pleasant Grove Rd., Bluff City, TN 37618

# NAB Labs All-digital AM Test Project

David H. Layer
National Association of Broadcasters
Washington, DC

**Abstract –** *Since 2012, NAB Labs has been conducting a number of field tests (and more recently, laboratory testing) of the HD Radio all-digital AM signal.[1] The purpose of this test project has been to characterize the digital coverage performance and interference behavior of the all-digital AM signal under a variety of conditions, with the goals of better understanding the capabilities and limitations of this signal and to develop a technical record in examining the feasibility of possible FCC authorization of an all-digital AM service. This paper provides a brief description of the all-digital AM signal, then offers a summary of some of the field test results on nine stations obtained by NAB Labs to-date, as well as a discussion of the lab tests being conducted, and discusses possible future test activities.*

## Introduction

AM and FM band digital radio broadcasting in the United States was authorized by the FCC in 2002, using the hybrid mode of the HD Radio™ in-band/on-channel (IBOC) system developed by iBiquity Digital Corporation. [1] This digital radio technology, standardized by the National Radio Systems Committee (NRSC) in 2005 as NRSC-5,[2] supports not only the hybrid mode of operation currently authorized for use (which includes both legacy analog and digital signal components) but also an "all-digital" mode (not currently authorized) that eliminates the analog portion of the signal and provides a number of benefits including improved robustness, a reduction in adjacent-channel interference, and a greater coverage area than the hybrid version of the system. [2]

At the end of 2014, nearly 25 million HD Radio receivers were in the marketplace and nearly 2000 radio stations were broadcasting an HD Radio signal. [3] As marketplace acceptance of this technology continues to increase, at some point broadcasters may consider introduction of the all-digital mode of operation. It has been generally accepted that an all-digital mode would not be introduced until market penetration of receivers was sufficiently high, since once broadcasters switch to all-digital operation, analog radio receivers (those not equipped to receiver the HD Radio signal) will go silent. Note that the vast majority of HD Radio receivers being sold are capable of receiving both hybrid and all-digital signals, with the only exceptions being a few low-power portable models (that are also FM-only).

Further, within the broadcasting industry there has been more interest in the all-digital version of the AM system than the all-digital version of the FM system because, for a variety of reasons, the hybrid AM system has not been widely deployed by broadcasters and has not received the same level of market acceptance as has the hybrid FM system. As a result, some AM broadcasters have been looking beyond hybrid to the all-digital AM system as a possible digital radio solution for the AM band.

Other than the technical information on the design of the all-digital AM system included in NRSC-5, there is little information in the public record on the performance and capabilities of this system.[3] The purpose of the test project reported on herein has been to add to this record by characterizing the digital coverage performance and interference behavior of the system under a variety of conditions, with the goals of better understanding the capabilities and limitations of this signal and to develop a technical record examining the feasibility of possible FCC authorization of an all-digital AM service.

## The HD Radio All-digital AM Signal

The all-digital AM signal consists of an unmodulated carrier which is surrounded by groups of orthogonal frequency division multiplexed (OFDM) digital subcarriers as shown in Figure 1. Some of the parameters of this signal are given in Table 1. This signal is referred to as the "MA3" service mode, and is presently designed to support a single audio channel (called the "main program service" or MPS) as well as supplementary data information (specifically, "program service data" or PSD and "station information service" or SIS).[4]

Part of the MA3 mode system specification includes an RF mask which constrains the spectral emissions.[5] This mask was designed based on a theoretical analysis of the MA3 mode of operation so as to minimize the impact of out-of-band (*i.e.*, beyond the ±10 kHz full bandwidth spectrum of the signal) emissions on adjacent-channel signals while

[1] Created in 2012, NAB Labs is an initiative of the National Association of Broadcasters (NAB), providing a platform for innovation, a venue for forging partnerships and testing new technology, and educational events to create awareness about over-the-air radio and television technology initiatives.

[2] Since its original adoption, the NRSC-5 Standard has been updated by the NRSC three times, most recently in 2011 (NRSC-5-C).

[3] Limited field tests were conducted by iBiquity in 2002 at stations WTOP-AM in Washington, DC and WD2XAM in Cincinnati, OH and reported on in [4]. The next engineering report on this system was not published until 2013, as part of the project being discussed in this paper. [5]

[4] Note that the hybrid AM signal is referred to as the "MA1" service mode.

[5] See [7], Section 4.5.4.

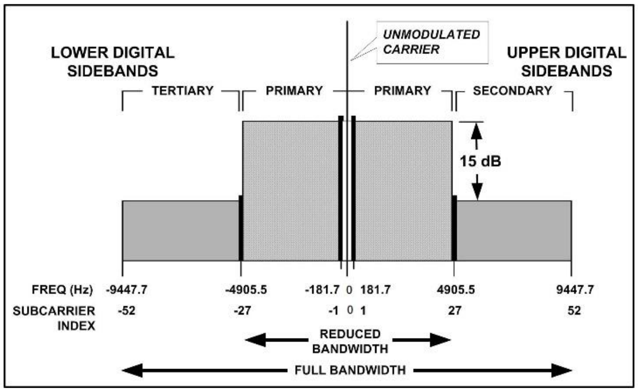



Figure 1. All-digital AM signal spectrum - from [6], Figure 5-4

simultaneously attempting to not overly constrain the signal. As will be discussed below, in implementing this signal at nine different radio stations as part of the field test portion of this project, currently available transmission equipment had some difficulty in meeting the RF mask as specified in [7].

Table 1. All-digital AM system parameters

| PARAMETER | VALUE: REDUCED BW CONFIG. | VALUE: FULL BW CONFIG. |
|---|---|---|
| RF bandwidth | ±5 kHz | ±10 kHz |
| Channel information rate | 20 kbps | 40 kbps |
| Digital subcarriers | ≈ 54 | ≈ 104 (54 from core plus 50 additional) |
| Main channel audio | Mono or parametric stereo | Two-channel stereo |
| % of signal power in unmodulated carrier[6] | 37% | 36% |
| Data broadcasting capabilities | Station information service (SIS), Program service data (PSD), Emergency alert system (EAS) | |

A broadcaster may transmit either the full bandwidth or the reduced bandwidth signal. The reduced bandwidth signal consists of just the unmodulated carrier and the primary digital sidebands (shown in Figure 1) while the full bandwidth signal includes the secondary and tertiary digital sidebands, as well.[7] Note that the audio signal received using all three digital sideband groups is considered "enhanced" audio, while the audio signal derived from just the primary digital sidebands is considered "core" audio. Under normal circumstances, assuming full bandwidth transmission, a receiver close to the transmitter will be able to successfully decode the entire MA3 mode signal, but as the receiver is moved farther away from the transmitter, a point will be reached where the secondary and tertiary digital sidebands will not have sufficient signal strength to be decoded and the receiver will at that point "blend" from enhanced audio to core audio.

Continuing away from the transmitter, there will then come a point where the primary digital sidebands are too weak (or too heavily interfered with) to be decoded and at that point the receiver will either mute or static will be heard corresponding to the noise and/or co-channel signal energy present.[8] Throughout this paper, this point will be referred to as the all-digital AM point-of-failure or simply POF. This is in contrast to the operation of the hybrid AM system which has an analog AM signal component to which the receiver "blends" when the (hybrid) digital signal components can no longer be received.

It should be noted that the greatest extent of coverage of the MA3 mode is determined by the coverage of the primary digital sideband components of the signal, and that the coverage of the core audio service will be the same whether the system is operated in full bandwidth or reduced bandwidth mode. The co- and adjacent-channel interference behavior of the full and reduced bandwidth modes will be different, of course, as will the RF mask compliance (since the more broadband full bandwidth signal will generate greater out-of-band emissions than will the reduced bandwidth signal).[9]

### Field testing of the All-digital AM Signal

Early field testing of the HD Radio AM system in all-digital mode was reported by iBiquity in April 2002. [4] Testing was conducted at two stations: WTOP-AM (1500 kHz, Washington, DC, class A, 50 kW, nighttime only), and WD2XAM (1660 kHz, Cincinnati, OH, class D, 10 kW, daytime only). For these early tests, the unmodulated carrier power was set to 50% of the total signal power which is higher than the level presently specified for the system (refer to Table 1).

The genesis of the field testing being reported on in this paper stems from when NAB Labs was approached by CBS Radio in 2012, offering to make AM station WBCN (1660 kHz, Charlotte, NC) available on a limited basis for all-digital AM testing, and providing an opportunity to begin developing a contemporary test record that would help educate the industry as to the capabilities of all-digital operation, develop all-digital operational parameters, and provide information which could be eventually submitted to the FCC for the purposes of obtaining permanent authorization for all-digital service. Subsequent testing of WBCN was conducted for both daytime and nighttime operation and for both indoor and mobile reception in December 2012 and the results of this

[6] The unmodulated carrier is used in the receiver to assist in signal recovery and is an essential part of the transmitted signal.
[7] Reference sidebands are also included in the signal, shown in Figure 1 as dark lines, and are not considered part of the primary, secondary or tertiary sideband groups.
[8] Whether a receiver mutes or static is heard at the point of core audio failure depends upon the specific design of the receiver. During the tests conducted under this project, receivers were encountered that exhibited one (and sometimes both) of these behaviors.
[9] All of the field test coverage results reported on herein were obtained with the system being operated in full bandwidth mode.

testing were presented at the 2013 NAB Broadcast Engineering Conference (BEC). [5]

Following the WBCN test, NAB Labs, in consultation with the NAB Radio Technology Committee (NABRTC, an NAB technical committee comprised of radio broadcast technical executives from NAB member companies), developed an extensive all-digital AM field test project plan, seeking to characterize the digital coverage performance of the all-digital AM signal under a variety of conditions. To that end, the NABRTC developed a list of characteristics for stations that should be included in this testing, seeking to balance the desire to develop as complete of a test record as possible with recognizing the practical constraints of budget and timeline on the test program. Table 2 is a list of the characteristics so identified, and in addition identifies the specific stations for each category that were ultimately tested under this project. Table 3 provides detailed information on the parameters of the nine tested stations, and Figure 2 shows the approximate location of each station.

A concern raised by the NABRTC in considering this test project was the amount of time needed for a station to broadcast the all-digital AM signal, since during that time the majority of listeners (those not using an HD Radio receiver) would not be able to receive the station's signal. Consequently, whereas the WBCN test was conducted using only a single test data collection vehicle, it was decided that subsequent tests would utilize multiple test vehicles operating simultaneously, resulting in a significant reduction in the required test time. Ultimately, NAB Labs assembled five "test kits" (described below) and for the remaining tests would operate from three to five test vehicles simultaneously at each test site.

Another difference between the WBCN test and the remaining tests involved the test vehicles and data collection receivers used. For WBCN, the only test vehicle used to collect coverage data was a specially modified Ford Focus owned by iBiquity (described in detail in [5]). The coverage data for WBCN was obtained using the Focus' in-dash receiver connected to the vehicle's built in antenna, however, this receiver also had a custom data interface (designed by iBiquity) utilizing the auto's "I2C" data bus allowing for connection to a laptop computer and collection of various receive signal parameters such as digital reception state (*i.e.*, digital signal acquired or not acquired), and in fact it was this reception state data signal that was used to establish the all-digital AM coverage for WBCN.

Table 2. Field test station categories established by NAB Radio Technology Committee

| CATEGORY | STATION(S) | COMMENTS |
|---|---|---|
| Non-directional antenna, expanded band | WBCN, WD2XXM | |
| Directional antenna | WNCT, WBT, WDGY, KKXA, KRKO | |
| Class A | WBT (twice) | |
| Lower-band (540-800 kHz) | WDGY | |
| Class D | WDGY | |
| Challenging facility | WSWW | Analog only station, converted for field test |
| Class C (local channel) | KTUC, WSWW | |
| Complex antenna array | KTUC, KKXA, KRKO | Diplexed single antenna (KTUC), diplexed array (KKXA, KRKO) |

Table 3. AM radio stations used in all-digital AM field testing

| NO. | STATION | OWNER | LOCATION | FREQ (kHz) | CLASS | PWR D/N (kW) | # OF TOWERS | ANTENNA | DATE(S) TESTED |
|---|---|---|---|---|---|---|---|---|---|
| 1 | WBCN | CBS Radio, Inc. | Charlotte, NC | 1660 | B | 10.0 / 1.0 | 1 | ND1 | 12/12 |
| 2 | WNCT | Beasley Broadcast Group | Greenville, NC | 1070 | B | 25.0 / 10.0 | 5 | DA2 | 7/13 |
| 3 | WBT | Greater Media, Inc. | Charlotte, NC | 1110 | A | - / 50.0 | 3 | DAN | 8/13, 3/14 |
| 4 | WD2XXM | Hubbard Radio / iBiquity Digital Corp. | Frederick, MD | 1670 | EXP† | 3.0 / 3.0 | 1 | ND1 | 10/13. 12/13 |
| 5 | KTUC | Cumulus Media | Tucson, AZ | 1400 | C | 1.0 / 1.0 | 1 | ND1 | 2/14 |
| 6 | WDGY | WRPX, Inc. | Hudson, WI | 740 | D | 5.0 / - | 3 | DAD | 6/14 |
| 7 | WSWW | West Virginia Radio Corporation | Charleston, WV | 1490 | C | 1.0 / 1.0 | 1 | ND1 | 7/14 |
| 8 | KKXA | CAAM Partnership, LLC | Snohomish, WA | 1520 | B | 50.0 / 50.0 | 4 | DAN | 10/14 |
| 9 | KRKO | S-R Broadcasting Co., Inc. | Everett, WA | 1380 | B | 50.0 / 50.0 | 4 | DAN | 10/14 |

*†EXPERIMENTAL*


Figure 2. All-digital AM field test locations (numbers refer to station numbers in Table 3)

Subsequent tests used a variety of Ford rental vehicles (including the Ford Edge, Ford Explorer, Ford Escape, and Ford Fusion) obtained at each location just prior to testing. In every case, the in-dash receiver and built-in vehicle antenna were used for data collection, however no custom data interface was available so instead the audio output from the receiver was connected to the data collection computer in the vehicle and analyzed to determine whether the receiver was acquiring digital audio. Simply stated, the receiver audio is monitored by the test computer and when audio is present, this is an indication of successful digital signal reception. When audio is not present (*i.e.*, muted or low-level "static") this is taken as an indication of loss of digital signal reception. The test computer software continuously logs the digital signal reception state versus vehicle position and creates a .kml data file which can then be imported into Google Earth for analysis.

One issue with this audio monitoring technique is that it becomes necessary to be able to distinguish between audio silence due to a pause or gap in program material (for

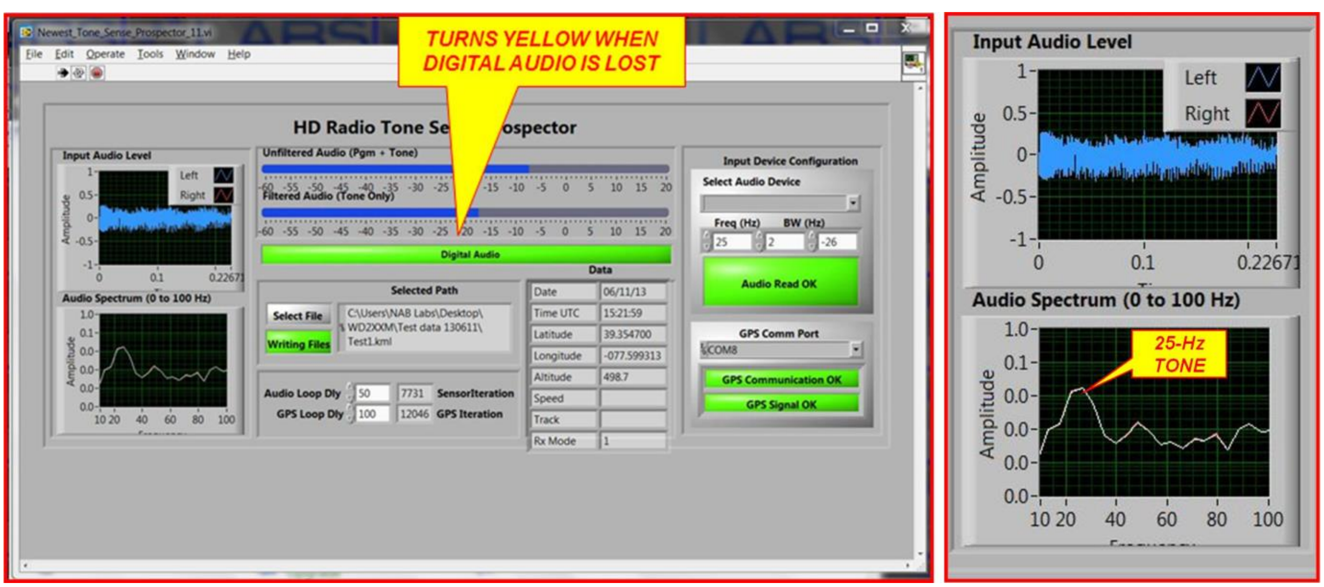



Figure 3. Field test data collection software user interface – main screen at left, detail at right shows the input audio level versus time (top graph) and frequency (lower graph) where the inserted 25-Hz tone is clearly visible.

example, “dead air” between segments) and silence resulting from loss of digital signal reception. To accomplish this, a low-level, barely audible 25-Hz tone was added into the digital audio signal path at the station, and the test computer software was configured to key on the presence or absence of the 25-Hz tone as the indicator for digital signal reception. Figure 3 is a screen shot of the data collection program used (written by iBiquity) and in the lower graph in the inset, the 25-Hz tone can be clearly seen. This tone provided a reliable indication of digital audio reception and, by extension, digital signal coverage.

Below is a general outline of the process and procedures used for conducting these field tests (additional specific information for particular stations, including any departure from the general outline given here, will be provided along with the specific station write-ups below):

- NAB Labs and the management personnel for the station under test selected test dates and times for testing so as to minimize the disruption to station operations. Once dates were selected, the station management obtained an experimental authorization from the FCC;
- NAB Labs and the station’s engineering staff then reached out to the appropriate transmitter equipment manufacturer to obtain on-site technical support during the field test. This would typically include installation and test of software upgrades to exciter and transmitter equipment necessary to support the MA3 mode of operation;
- NAB Labs and the station’s engineering staff recruited personnel for driving the test vehicles (up to five vehicles per station were used), arranged for rental of the necessary number of vehicles, and developed the specific test routes to be used for testing;
- Approximately two weeks before the start of testing, NAB Labs shipped out equipment needed for the testing including five vehicle test kits (described below), digital audio recorders, two Conex LFG-1000 tone generators (main and backup, used for generating the 25-Hz test tone described above), a PI-4100 field strength meter, and an HP-8563E spectrum analyzer;
- Approximately one week out, the station engineer installed the Conex tone generator into the station’s digital audio path and verified proper operation;
- The day before the start of testing, NAB Labs installed the test kits into the data collection vehicle and confirm proper operation. Each kit included a test computer and external battery to allow for extended operation (up to 10 hours), sound card, GPS receiver, audio transformer (providing impedance transformation from the radio receiver’s speaker wire to the sound card input), and various cables and connectors. A test kit installed in a Ford Edge vehicle is shown in Figure 4;
- Data collection took place during daytime and/or nighttime station operations depending upon the particular station. All-digital AM signal power was set by referring to the transmitter power output meter and by monitoring a current meter at the antenna base (or common point for stations with more than one tower). With the transmitter operating at licensed analog power, the base (or common point) current would be noted, then the transmitter would be switched to all-digital mode and the transmit power would be adjusted to achieve the same current reading. Photographs of the spectrum of the transmitted signal as observed on the HP-8563E spectrum analyzer were obtained (see Figure 5).


Figure 4. Field test data collection system as deployed in Ford Edge vehicle.

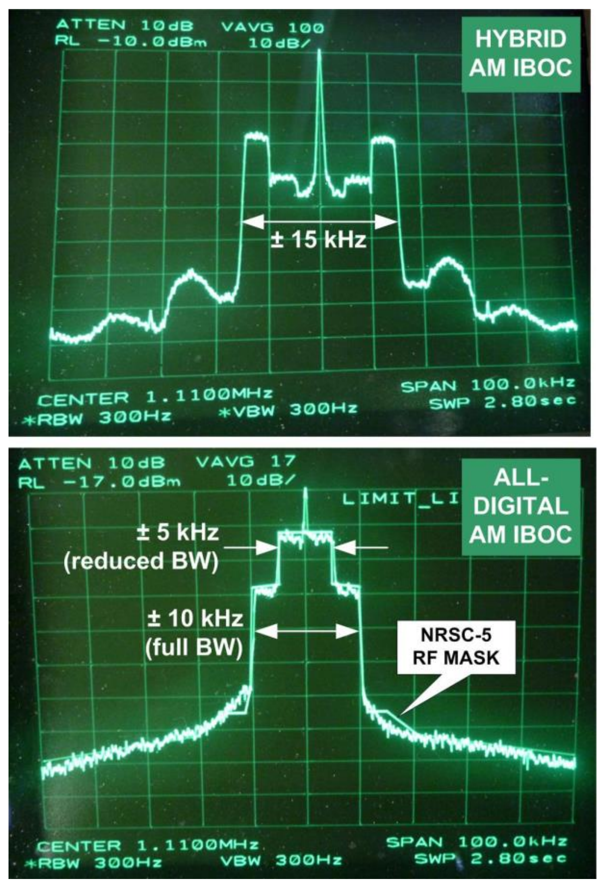



Figure 5. Photographs of typical hybrid AM (top) and all-digital AM (bottom) signal spectra as observed from monitor points inside the transmission facility, using the HP 8563E spectrum analyzer.

- Field test routes typically started at the transmitter site and proceeded away in a radial direction. Once the transmitter was switched to all-digital mode, the test data collection software was started and the vehicle operator drove out to and beyond the all-digital POF as indicated by the test data collection software.[10] Then, a new test run was initiated starting from the furthest point driven, back to the transmitter site, and time permitting, another test route was immediately run in a similar fashion;
- Numerous audio recordings were made of the received audio, using a Tascam DR-2d recorder. Of primary interest was collection of audio recordings of the analog signal obtained at the all-digital POF, since these recordings represent the audio quality of the analog signal at the approximate point where the digital audio signal is lost. Also useful are audio recordings of the interference environment existing at POF, made by recording while momentarily turning off the transmitter for the station under test. In some cases, these recordings were made during the all-digital coverage data collection process, by having all test crews identify and then wait at the POF; once all crews were in place, the transmitter would then switch between all-digital, analog, and no signal over the course of a few minutes while audio recordings (and field strength measurements, discussed below) were made. When such a coordinated effort was not possible, a second trip to the all-digital POF was taken (typically the next day) except this time with the transmitter operating in analog mode, and a recording at the exact POF coordinates previously identified was obtained for the analog signal;
- In addition, numerous field strength measurements were obtained at or near the all-digital POF in an attempt to determine the field strength associated with loss of all-digital signal reception. These are discussed in greater detail below;
- For some stations, coverage data were also collected for the hybrid AM (MA1) mode of operation, to provide a basis for comparison with MA3 operation along the same test routes. These MA1 tests were done separately from the MA3 tests, usually after MA3 testing was completed, but using the same test software. For the MA1 tests, the 25-Hz tone was added to the digital audio path only, so that when the test receiver blended to analog the tone would disappear and the test data software would register a loss of digital signal reception;
- At the conclusion of testing, the equipment in the test vehicles was uninstalled, the Conex tone generator was removed from the station and all NAB Labs equipment was retrieved and shipped back. Typically the software upgrades made to the station equipment by the transmitter manufacturer were retained since these were usually compatible with analog and MA1 mode operation.

A summary of the all-digital AM field test results is provided in Table 4. Digital coverage data obtained at each test station is presented in the figures below, as is relevant station-specific information:

**WBCN** – coverage data for WBCN is taken from [5] and included here for sake of completeness.[11] Figure 6 presents the daytime and Figure 7 presents the nighttime all-digital AM coverage for WBCN. As previously mentioned, there are a number of differences between how the data were collected for WBCN compared to the other stations tested under this project, including the use of only a single vehicle and the use of a specially-modified in-car receiver for determination of the digital coverage area.

**WNCT** – this was the first station for which multiple test vehicles were run simultaneously and at which the 25-Hz test tone and test tone-detecting data collection software were utilized. Daytime coverage results for WNCT are shown in Figure 8 and nighttime coverage results in Figure 9.

Table 4. Field test summary of results. POF ranges are from the transmitter to the observed POFs for each station.

| | | | | DAYTIME | | NIGHTTIME | | |
|---|---|---|---|---|---|---|---|---|
| STATION | FREQ (kHz) | CLASS | PWR D/N (kW) | POF RANGE - DAY (mi) | CORRESPONDING ANALOG PREDICTED CONTOUR (mV/m) | POF RANGE - NIGHT (mi) | NIF (mV/m) | OUT TO NIF? |
| WBCN | 1660 | B | 10.0 / 1.0 | 26 - 45 | 0.5 - 0.1 | 10 - 14 | 5.1 | YES |
| WNCT | 1070 | B | 25.0 / 10.0 | 25 - 68 | > 0.5 | 4 - 20 | 53 | YES |
| WBT | 1110 | A | - / 50.0 | (not measured) | | 10 - 46 | 5 | YES |
| WD2XXM | 1670 | EXP | 3.0 / 3.0 | 35 - 50 | 0.5 - 1.0 | 15 - 25 | 4.5 | YES |
| KTUC | 1400 | C | 1.0 / 1.0 | 29 - 48 | 2.0 - 0.5 | 8 - 13 | 20.8 | YES |
| WDGY | 740 | D | 5.0 / - | 30 - 78 | 2.0 - 1.0 | (n/a) | | |
| WSWW | 1490 | C | 1.0 / 1.0 | 12 - 18 | 1.0 - 0.5 | 2 - 5 | 25 | YES |
| KKXA | 1520 | B | 50.0 / 50.0 | 17 - 57 | 2.0 - 0.5 | 11 - 28 | 44.6 | YES |
| KRKO | 1380 | B | 50.0 / 50.0 | 21 - 48 | 2.0 - 1.0 | 6 - 31 | 2.4 | YES† |

*†COVERAGE OUT TO ACTUAL NIF NOT PREDICTED NIF*

[10] Note that the coordinates of the POF location could be identified during data post-processing by inspection of the .kml data file resulting from the data run. Often times the vehicle operator would also make note of the POF coordinates during the test run, noting the coordinates from the test computer display screen (see Figure 3).

[11] Also in [5] are the results from indoor testing.

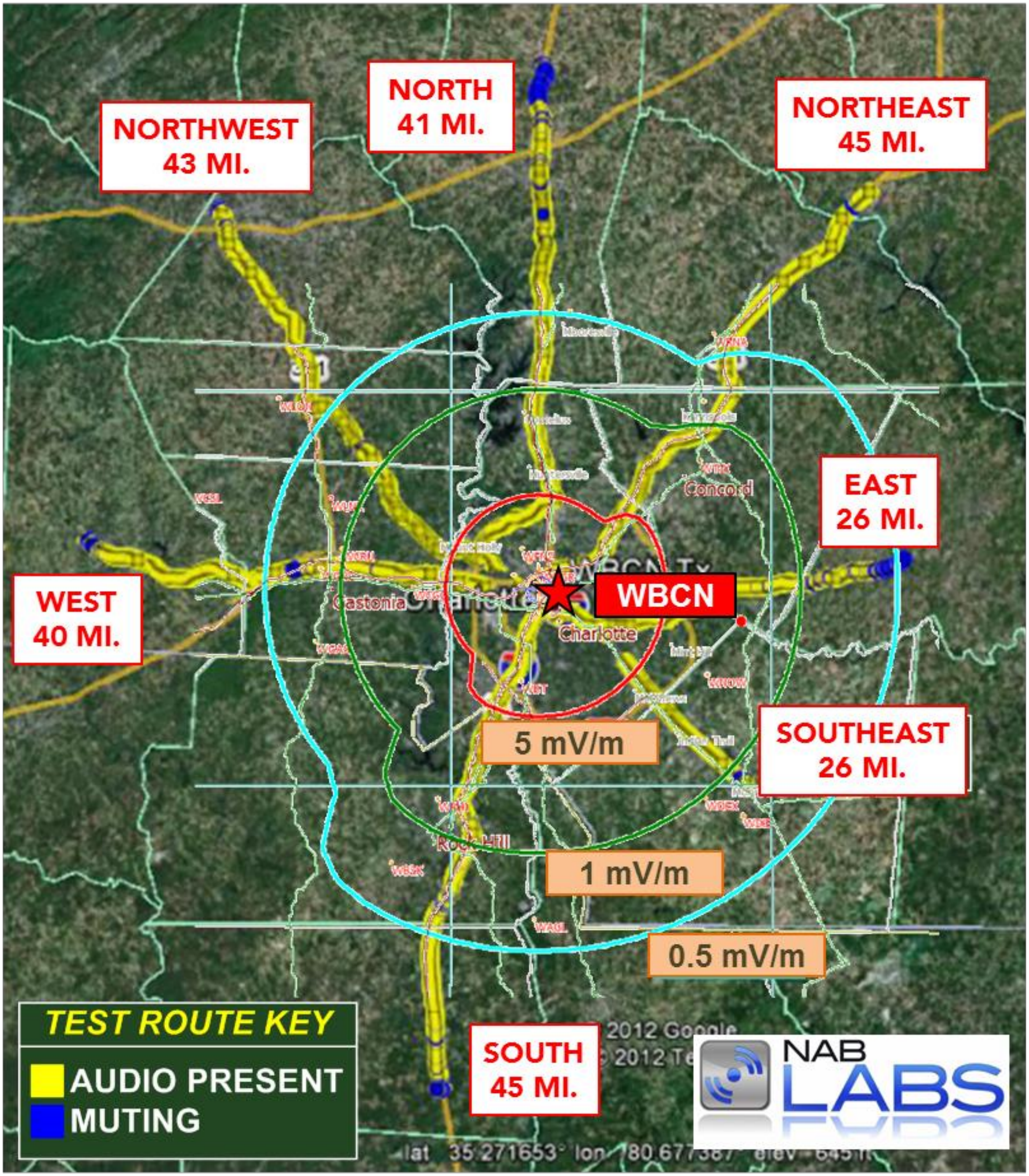



Figure 6. WBCN daytime all-digital AM coverage results (predicted analog contour shown)

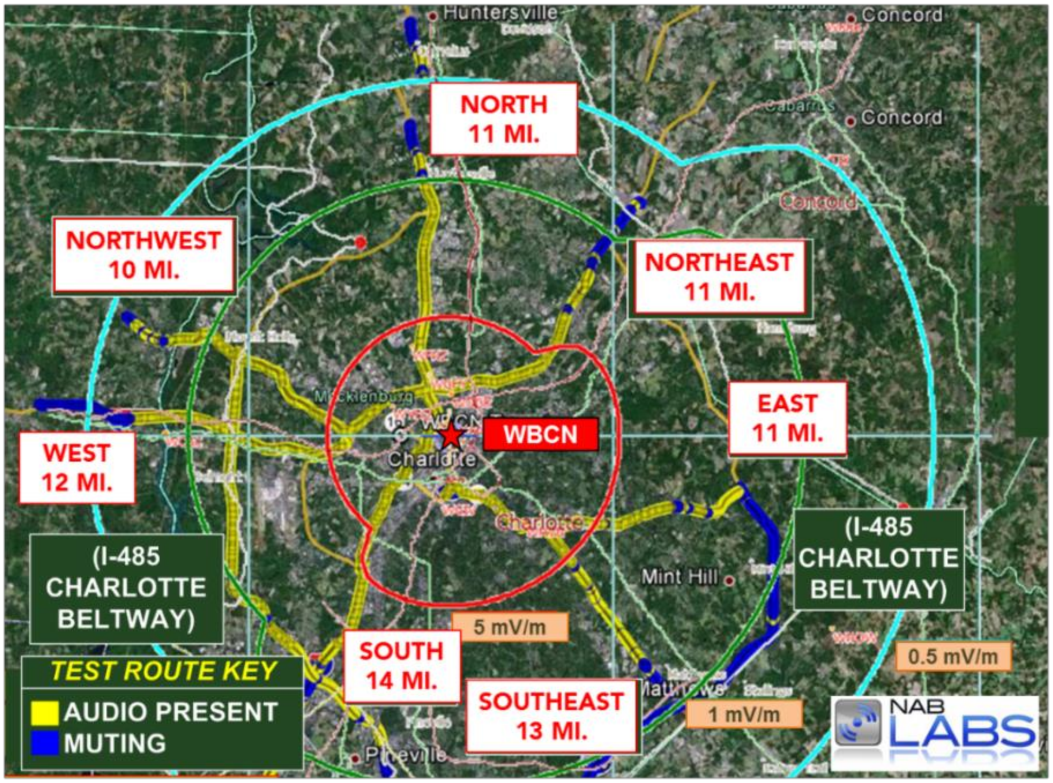



Figure 7. WBCN nighttime all-digital AM coverage results (predicted analog contour shown)

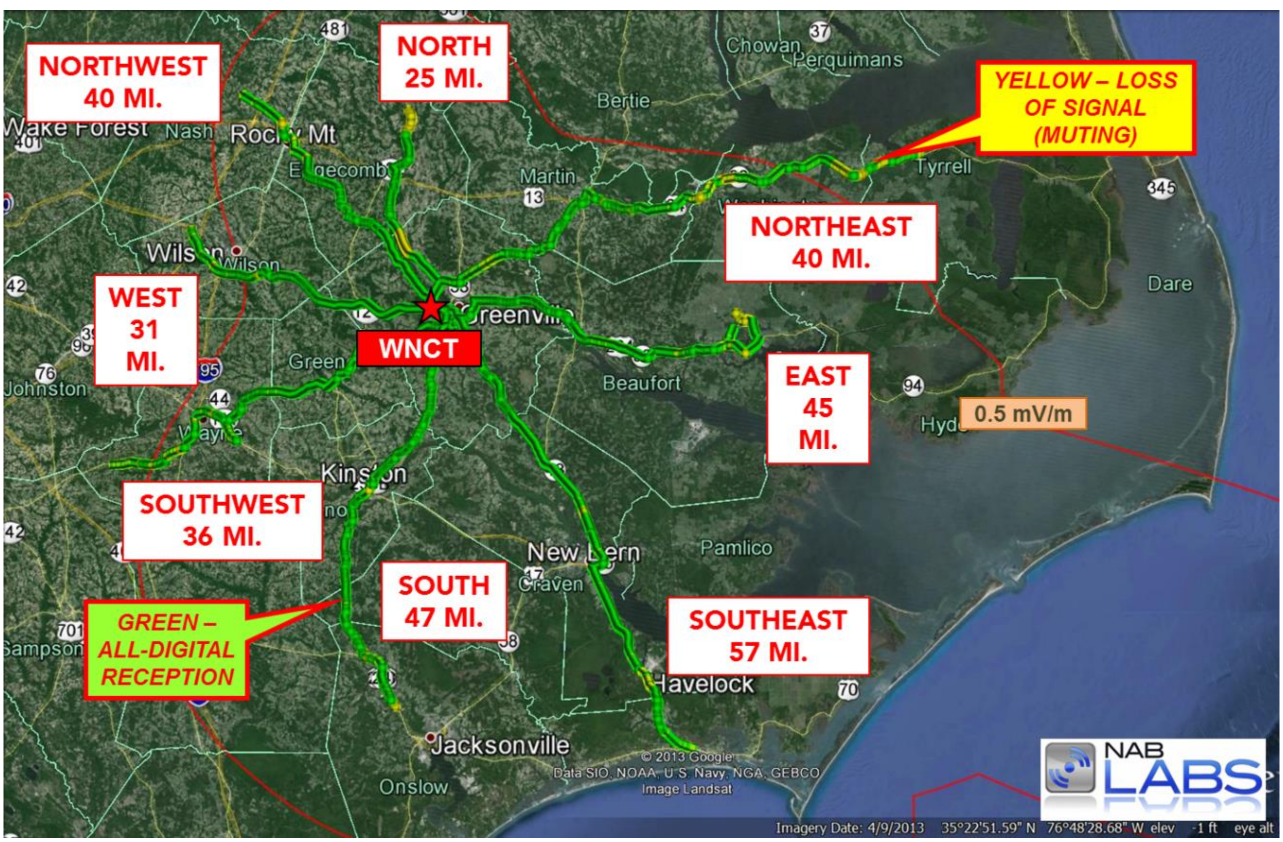



Figure 8 WNCT daytime all-digital AM coverage results (predicted analog contour shown)

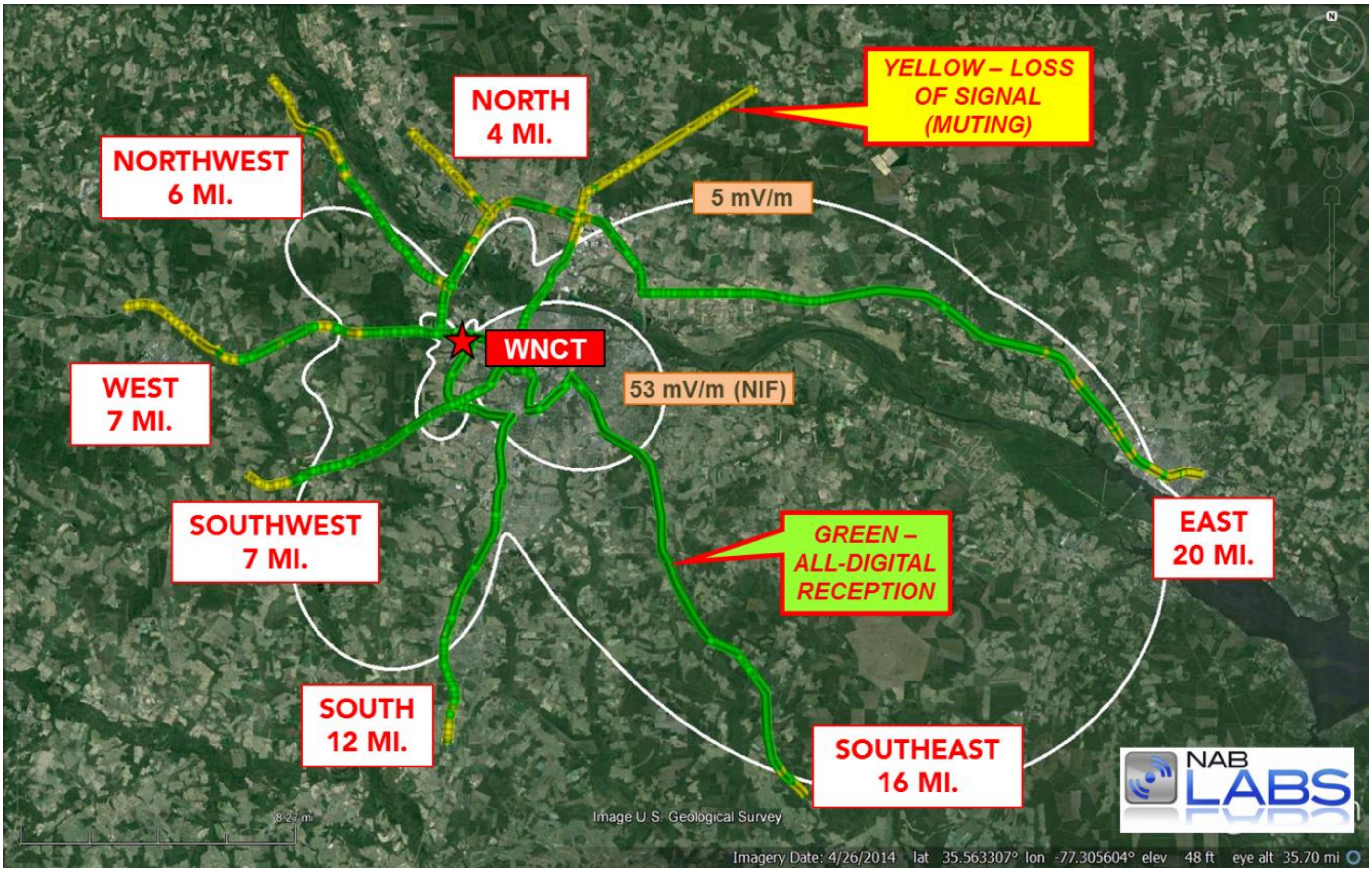



Figure 9. WNCT nighttime all-digital AM coverage results (predicted analog contours shown)

**WBT** – WBT is the only class A station tested as part of this project, and was tested only for nighttime all-digital AM coverage. In August 2013, WBT was operated in all-digital mode on two consecutive nights for four hours each night, from 1-5AM. The coverage results obtained during that test were poorer than anticipated and it was suspected that there was unauthorized interference on the channel. It was also determined afterwards that first-adjacent channel stations on 1100 and 1120 kHz were operating in hybrid AM mode and there was a possibility that the primary digital sidebands from those adjacent channel signals were also impacting the all-digital AM performance observed at WBT.

During the August 2013 test a number of long-distance listening observations were made (see Figure 10). Reports (and audio recordings) of listening in Boston, MA, Syracuse, NY, Fairfax, VA, Sarasota, FL and others were submitted, and some of these recordings captured the switchover from analog to all-digital AM broadcasting. The ability to receive the all-digital AM signal at long distances varied significantly from the first night to the second night, which is consistent with the behavior of skywave medium-wave signals.

A subsequent test of WBT was conducted in March 2014 and improved results were obtained. During the March 2014 test, the first-adjacent channel signals mentioned above temporarily ceased hybrid AM operations and this is thought to have been a factor in the improved performance. Also, there appeared to be less co-channel interference than was present during the initial test in August. Figure 11 presents the all-digital AM nighttime coverage observed at WBT in March 2014.

Observations of the hybrid AM performance of WBT were also obtained during the March 2014 test, subsequent to the all-digital data collection. Figure 12 is a comparison of the nighttime performance of hybrid (MA1) and all-digital modes (MA3), showing that the all-digital coverage exceed the hybrid coverage by approximately 50 to 70%. While it was not possible to obtain daytime coverage date for WBT in all-digital mode, Figure 13 shows a comparison of WBT hybrid AM performance for daytime and nighttime.[12] These results suggest that the daytime coverage for WBT using all-digital would be extensive, assuming that it would exceed the hybrid coverage by 50 to 70% as did the nighttime coverage.

**WD2XXM** – this is an experimental transmission station operated by iBiquity using the facilities of station WWFD (820 kHz, Braddock, MD, class B, 4.3 kW daytime, 430 W nighttime, Hubbard Broadcasting). WWFD utilizes a two-tower array but only one tower is used during the daytime; the unused tower is made available to iBiquity for daytime operation of WD2XXM on 1660 kHz. Figure 14 shows the daytime all-digital AM coverage obtained for WD2XXM. With the cooperation of Hubbard, WWFD used a single tower one night in December 2013 to allow for a nighttime test of WD2XXM (using the same tower as that used for daytime operation), resulting in the performance shown in Figure 15.

A co-channel traveler's information service (TIS) channel was encountered in Gettysburg, PA, on the daytime north test run and it is presumed that this interferer was largely responsible for the all-digital POF on this route. It was interesting to observe on the return trip to the station from Gettysburg, how the all-digital AM signal was re-acquired even at the point where the TIS signal was still being strongly received by analog receivers and was clearly audible. This observation is consistent with receiver behavior observed in lab testing (discussed below) whereby a weaker all-digital signal is sometimes acquired in the presence of a stronger analog co-channel signal.

**KTUC** – the first station west of the Mississippi tested under this project, KTUC was also the first class C station to be tested as well. Daytime coverage performance for this station is shown in Figure 16 and nighttime in Figure 17. Some field strength data obtained at KTUC is discussed below in the section on field strength measurements.

During the day, on every route, the test vehicles were well into the desert surrounding the Tucson market before reaching the all-digital POF, even on the northwest route (heading directly towards Phoenix) which was on a direct line between KTUC and Phoenix co-channel station KSUN located approximately 100 miles away. At night, the all-digital coverage was more limited than experienced on other (non-class C) stations, and this is attributed to the high predicted nighttime interference-free (NIF) contour of 20.8 mV/m. It was observed that at night, the analog signal existing at the all-digital POF (when the station was in analog broadcast mode) was quite listenable and extended for some distance beyond the all-digital POF location.

**WDGY** – with the lowest carrier frequency (740 kHz) of any station tested under this project, this station was predicted at the outset to have exceptional coverage and in fact the farthest measured distance to all-digital POF was here (north route, with POF at 78 miles from the transmitter). Figure 18 is the coverage data obtained from this daytime-only station.

Hybrid AM measurements were also made at WDGY at the conclusion of the all-digital test runs; Figure 19 is a comparison of the hybrid AM (MA1) performance to the all-digital (MA3) performance on a test route comprising the interstate loop surrounding the cities of Minneapolis and St. Paul, Minnesota. On this test route the all-digital AM performance was exceptional with not a single instance of digital signal loss. In contrast, the hybrid AM performance along this route demonstrated significant blending to analog, as close as a few miles from the transmitter (in the MA1 map of Figure 19, note the yellow "spot" on the test route, just above and to the right of the words "St. Paul;" this was a brief blend to mono experienced when the test vehicle drove under a concrete overpass), and more significantly on the northwestern parts of the route, where one issue included a "zig-zagging" high voltage transmission line that crisscrossed the highway for a number of miles.

[12] Note that for the hybrid daytime tests, WBT was operating with its nighttime antenna during daytime hours to provide a direct comparison to the nighttime hybrid coverage.

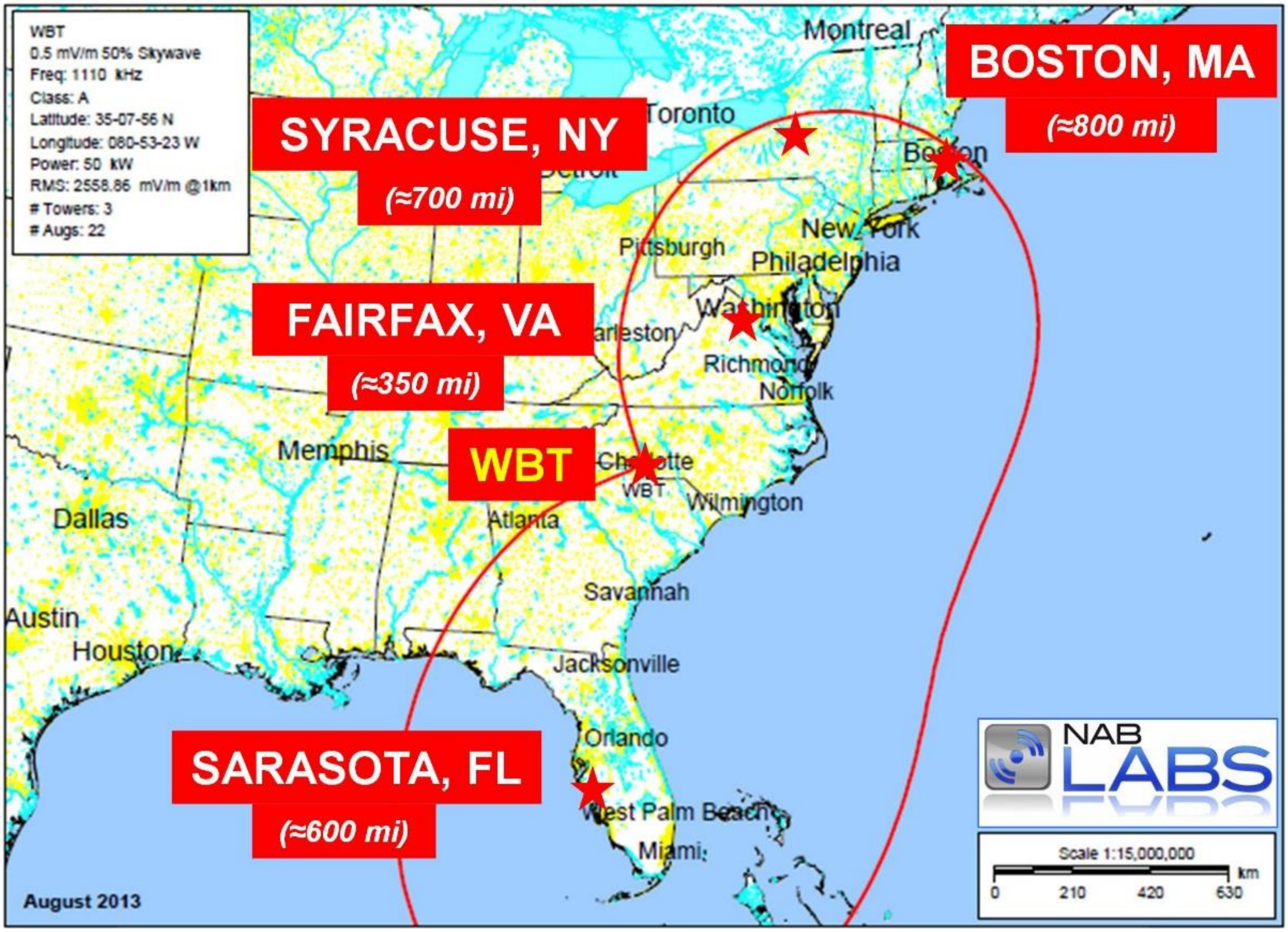



Figure 10. Map showing WBT computed 0.5 mV/m nighttime 50% skywave contour and locations where nighttime long-distance listening of the all-digital AM signal occurred (distances in parentheses are distances from the WBT transmitter)

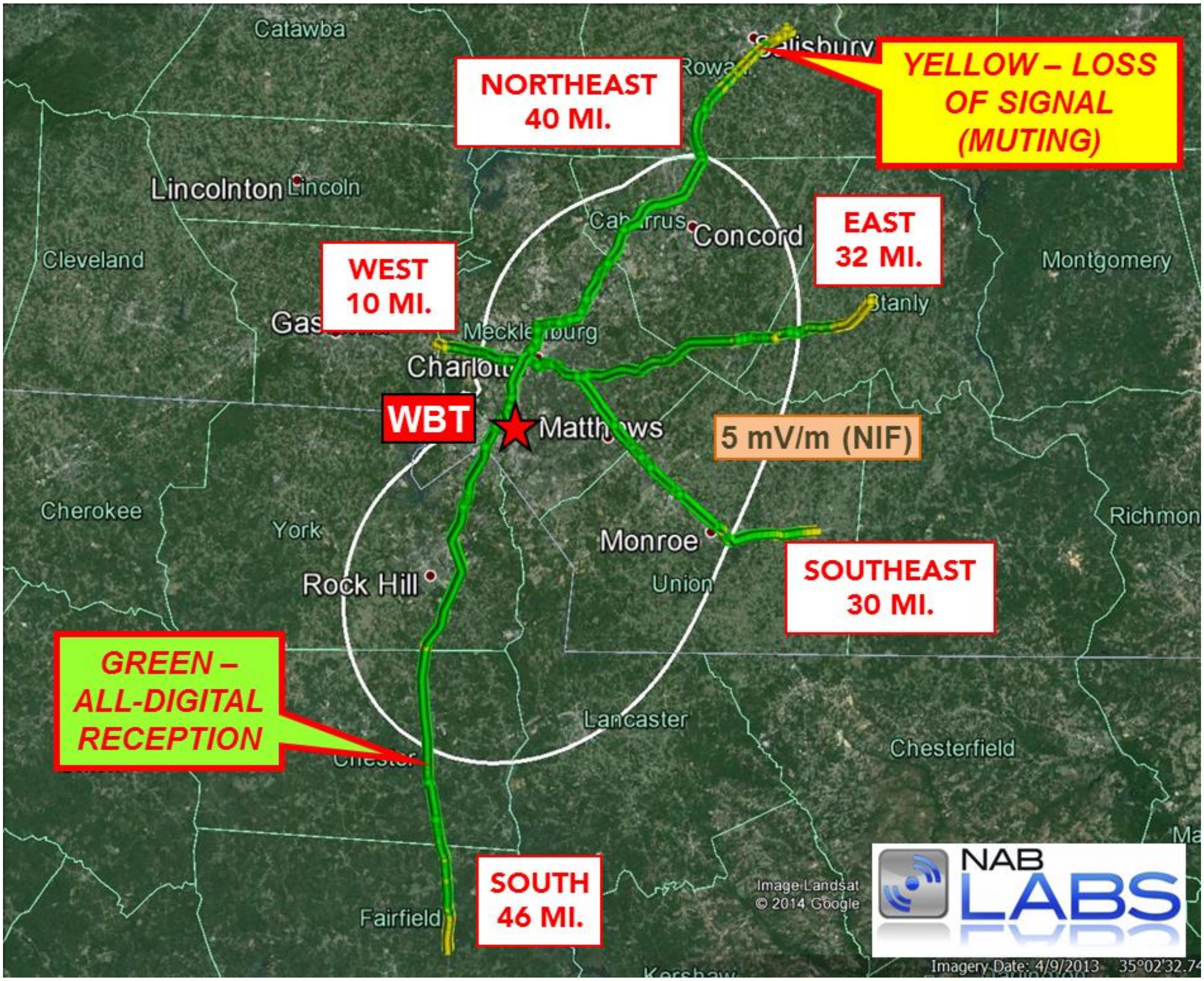



Figure 11. WBT nighttime all-digital AM coverage results (predicted analog contour shown)

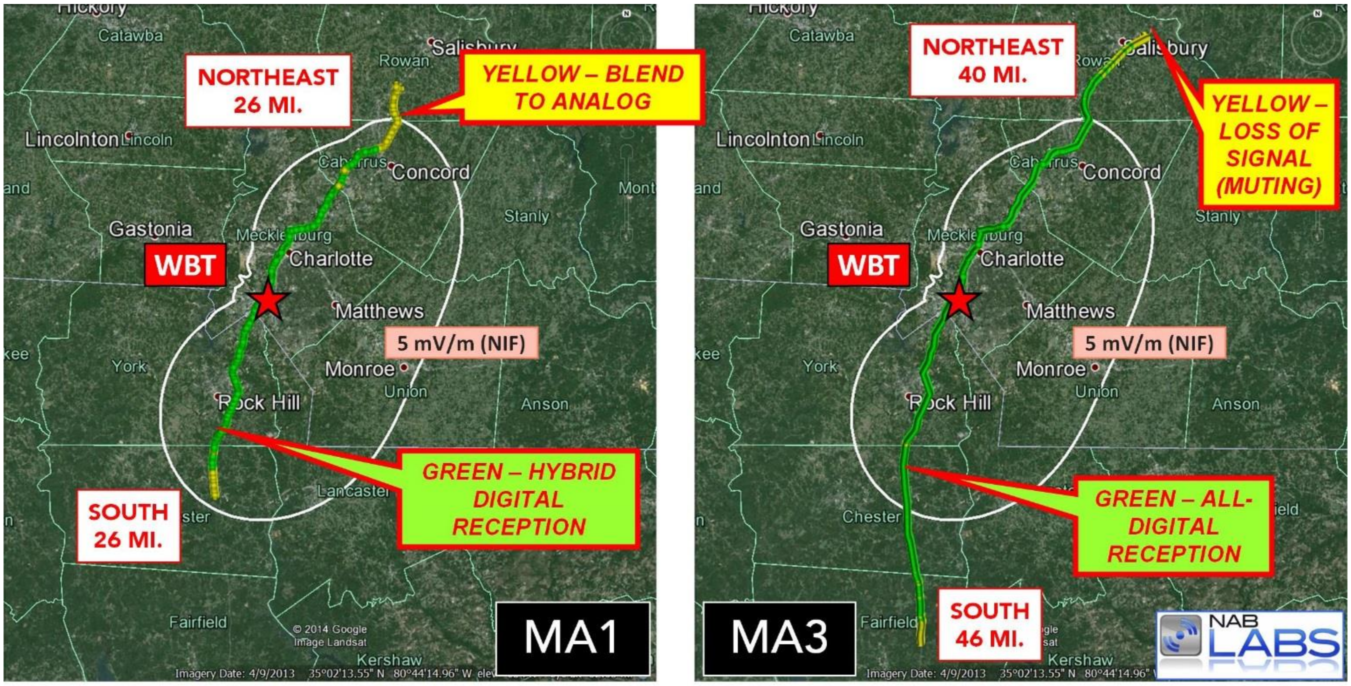



Figure 12. Comparison of WBT nighttime performance, hybrid AM (MA1) mode (on left) versus all-digital AM (MA3) mode (on right)

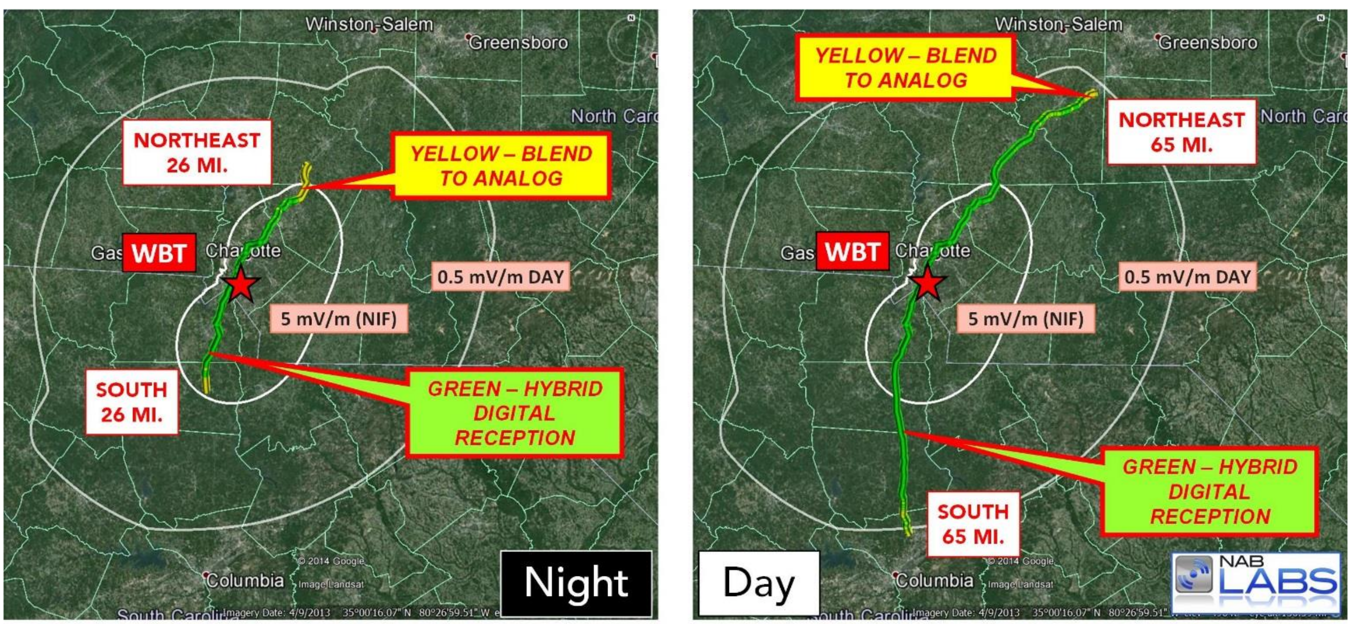



Figure 13. Comparison of WBT hybrid AM (MA1) mode performance, night (on left) versus (day (on right)

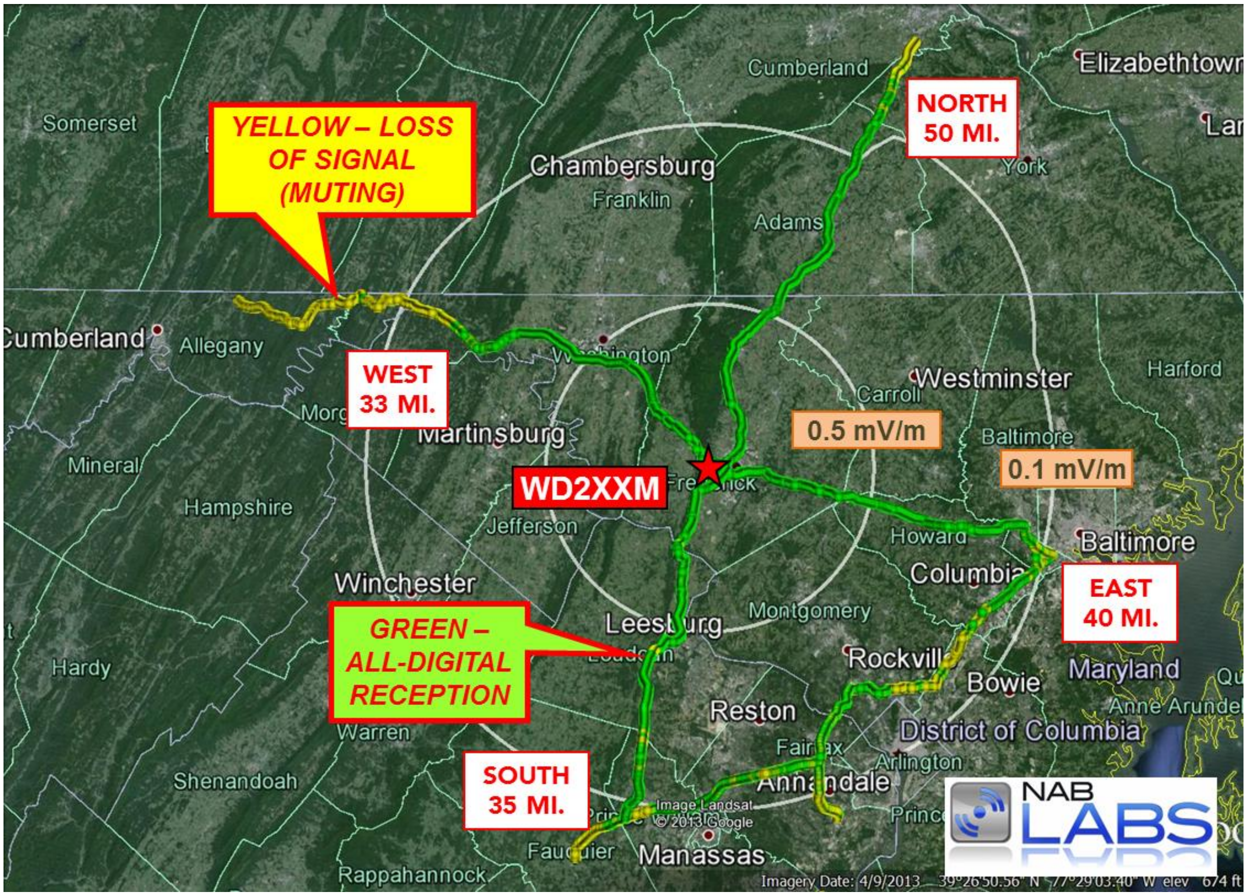



Figure 14. WD2XXM daytime all-digital AM coverage results (predicted analog contours shown)

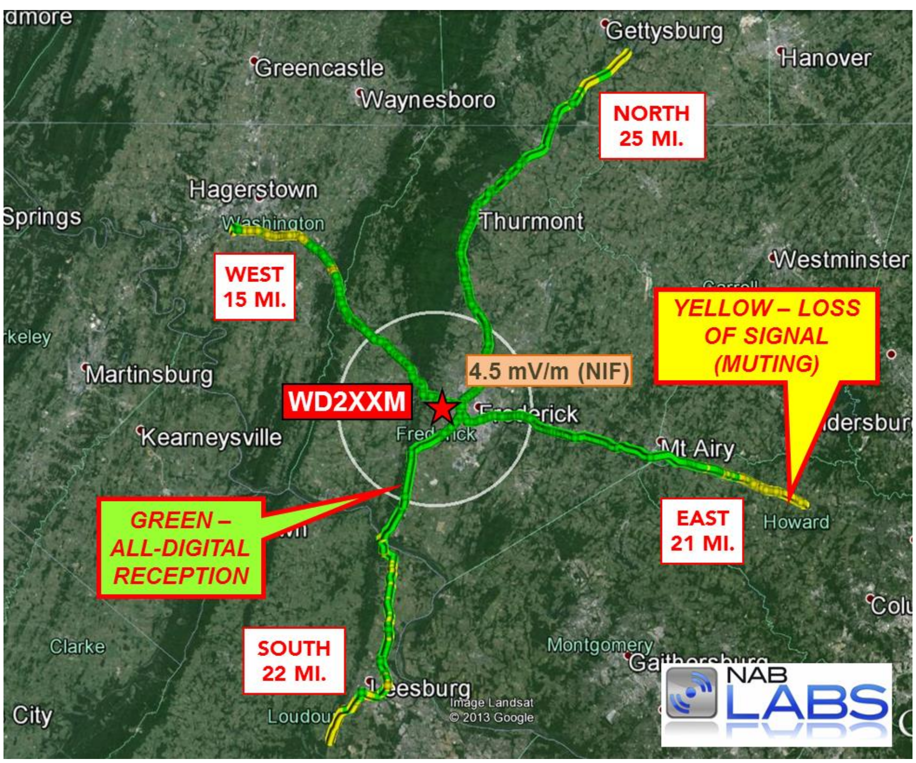



Figure 15. WD2XXM nighttime all-digital AM coverage results (predicted analog contour shown)

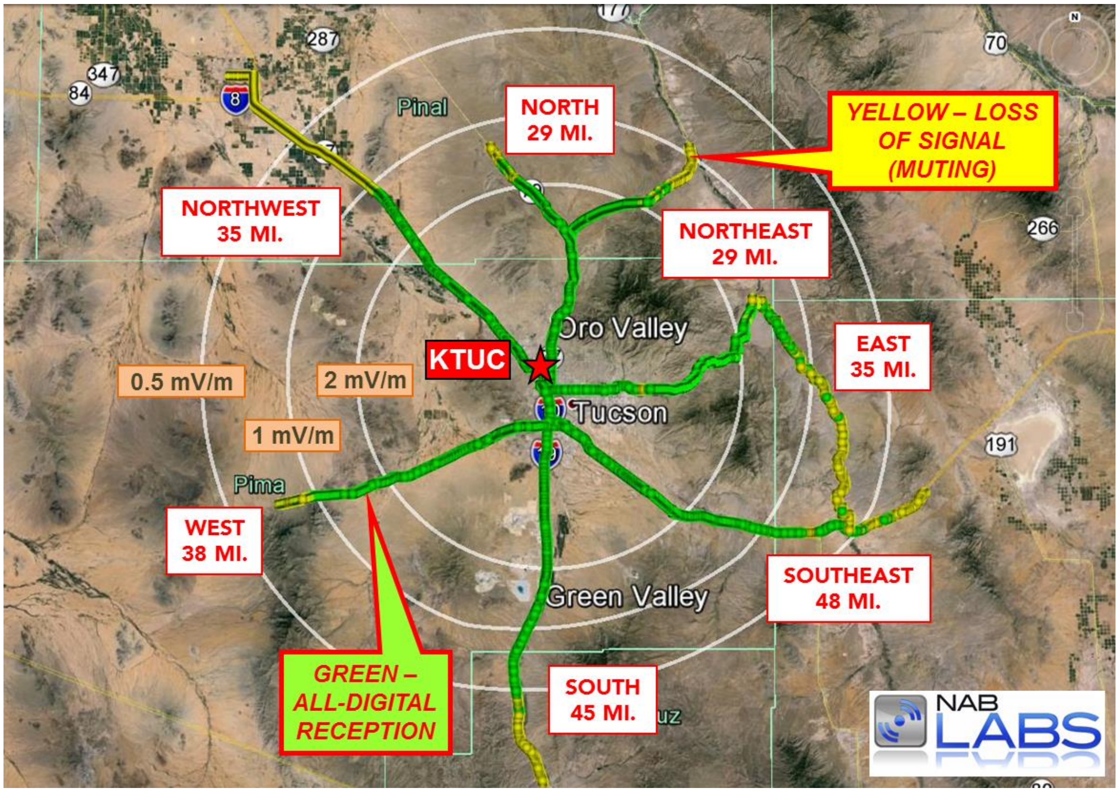



Figure 16. KTUC daytime all-digital AM coverage results (predicted analog contours shown)

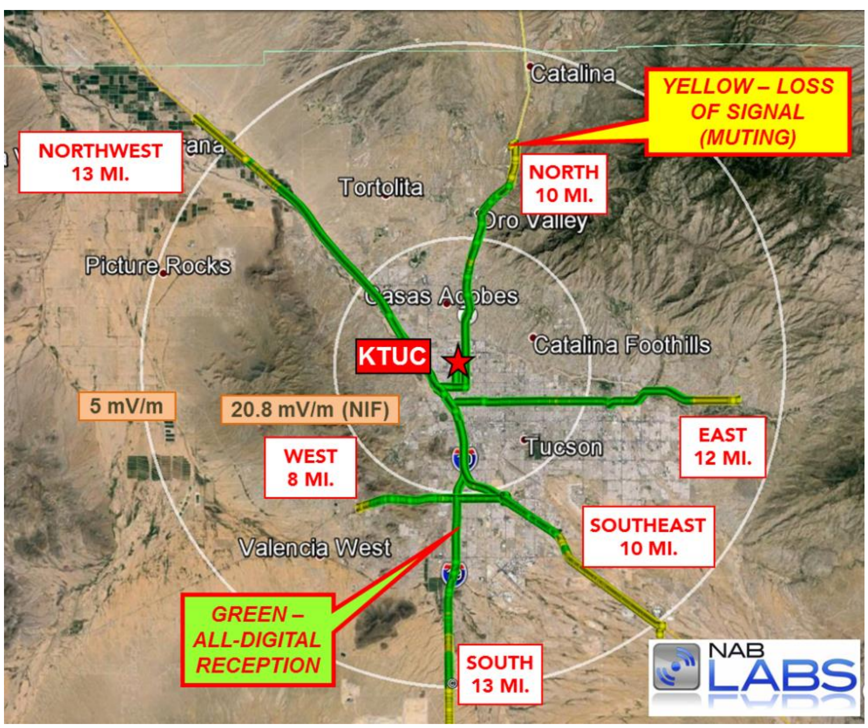



Figure 17. KTUC nighttime all-digital AM coverage results (predicted analog contours shown)

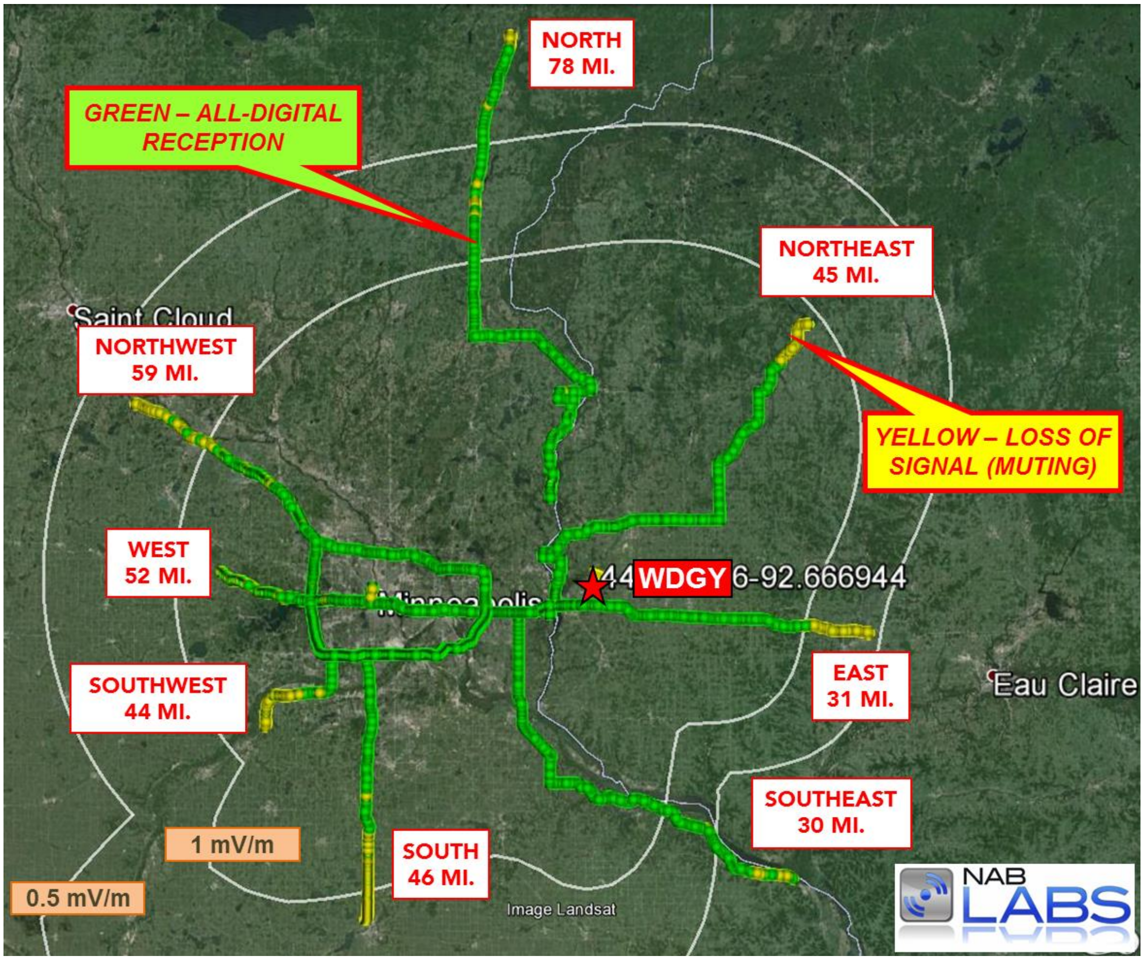



Figure 18. WDGY daytime all-digital AM coverage results (predicted analog contours shown)

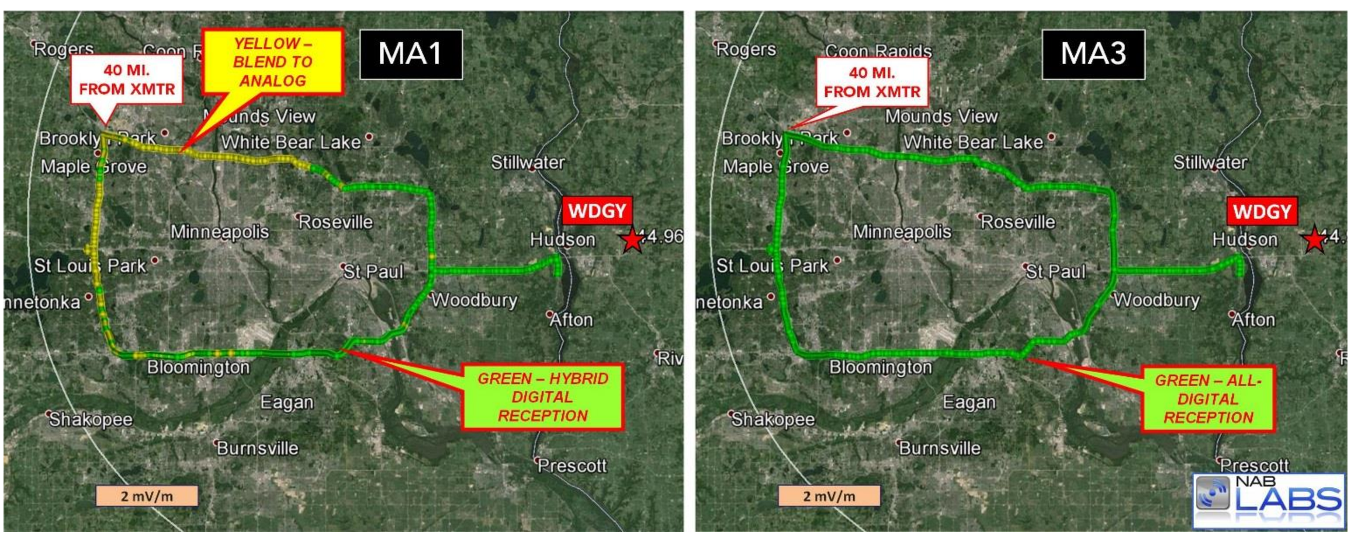



Figure 19. Comparison of WDGY daytime performance, hybrid AM (MA1) mode (on left) versus all-digital AM (MA3) mode (on right)

Since WDGY is a music format station ("oldies"), one of the test vehicles was set up for stereo audio recording and a number of stereo recordings were made, including one with a continuous, uninterrupted 1 hour, 28 minute length as the vehicle was driven from the transmitter along the southeast route. The purpose of this long recording was to capture the listening experience of the all-digital AM signal along a test route radial. For this recording, the first 59 minutes and six seconds were completely unimpaired, and from that point until 20 minutes later only three brief losses of digital audio reception were experienced. During the final eight minutes of the recording these "dropouts" became more frequent until finally the all-digital POF was reached and the recording was ended. NAB Labs is presently creating a video file which combines this audio recording with a moving map display corresponding to the approximate location of the test vehicle at each point in the recording, which will be made available to interested parties when completed, providing an opportunity to "experience" the all-digital AM reception for this route.

**WSWW** – prior to the start of testing, and with the cooperation of testing partners Kintronic Labs and Nautel, WSWW was temporarily converted from an analog-only station to an HD Radio transmission-capable station. This was the only station tested under this project that was not already capable of supporting digital transmission, and in fact one of the goals of the test project was to perform a digital "conversion" so as to assess the complexity (and potential for success) of an all-digital conversion. It should be noted that converting a station to all-digital AM operation is in theory less complex that doing a hybrid AM conversion since the constraints on the antenna system are relaxed. This is due to the fact that while the hybrid AM system requires a ±15 kHz RF bandwidth, an all-digital AM system has an RF bandwidth requirement of either ±10 kHz (for a full bandwidth implementation) or ±5 kHz (for a reduced bandwidth implementation).

The present WSWW transmission site was constructed in 1947, at which time the antenna tuning unit (ATU) and tower were installed; both of these items are scheduled for replacement in the next few years. Converting WSWW to all-digital operation for the purposes of the NAB Labs testing involved installation of the following items: an antenna tuning unit (ATU) optimized for digital operations, and an HD Radio-capable exciter and transmitter. Figure 20 shows the existing (top photo) and loaner (bottom photo) ATUs for WSWW. This station conversion proceeded without incident and was accomplished in a single day. At the conclusion of the testing, the station was restored to its original configuration without consequence.

Once converted, all-digital operations commenced and station performance was characterized for daytime (Figure 21) and nighttime (Figure 22) operations. As was true for KTUC (discussed above), at night, the all-digital coverage was more limited than experienced on other (non-class C) stations, and this is attributed to the high predicted nighttime interference-free (NIF) contour of 25 mV/m. Also, as with station KTUC, it was observed that at night, the analog signal existing at the all-digital POF (when the station was in analog broadcast mode) was quite listenable and extended for some distance beyond the all-digital POF location.

WSWW offered an opportunity for an investigation into the impact of an all-digital AM station on its analog co-channel neighbors. Figure 23 is a map showing WSWW and the four nearest co-channel stations – WMOA (Marietta, Ohio, 75 miles from WSWW), WSGB (Sutton, West Virginia, 53 miles), WAEY (Princeton, West Virginia, 73 miles), and WSIP (Paintsville, Kentucky, 73 miles). As part of this test, four test vehicles were driven to the numbered locations shown in Figure 23, and once all in place, audio recordings of the co-channel stations were made while WSWW was switched between all-digital, analog, and no signal transmission modes.

Figure 20. Existing (top photo) and loaner (lower photo) antenna tuning units (ATUs) at station WSWW

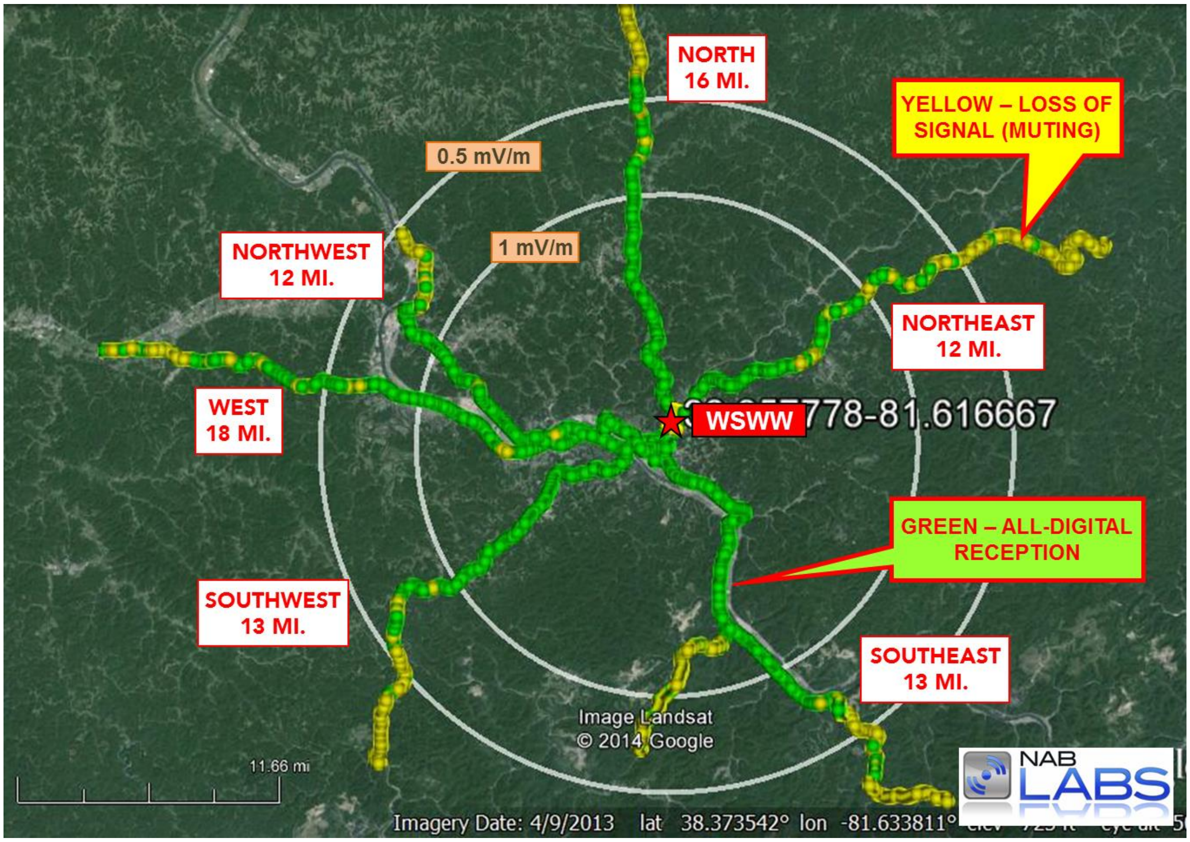



Figure 21. WSWW daytime all-digital AM coverage results (predicted analog contours shown)

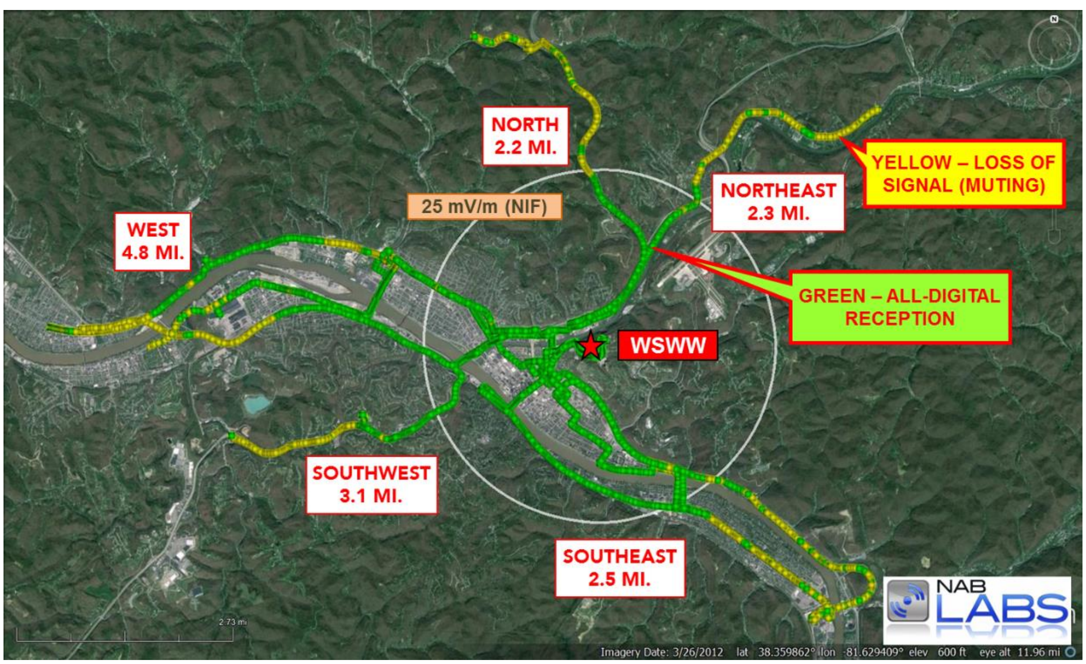



Figure 22. WSWW nighttime all-digital AM coverage results (predicted analog contour shown)

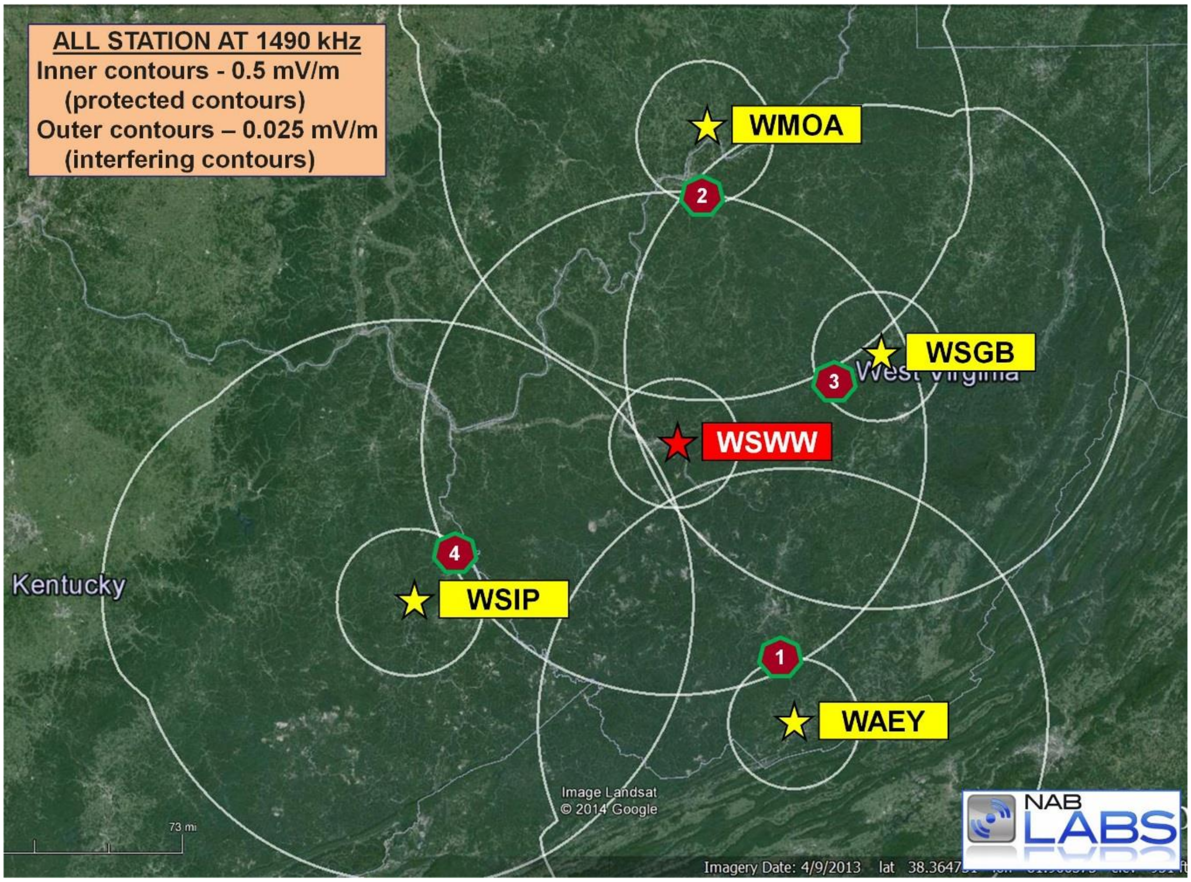



Figure 23. Co-channel stations near WSWW. Numbered points indicate locations where audio recordings were made of the co-channel signal with WSWW operating as both an analog and an all-digital AM interferer

Analysis of these audio recordings revealed that in each case, the impairment to the co-channel station was essentially equivalent irrespective of whether WSWW was operating with an analog or an all-digital AM signal.

**KKXA and KRKO** – these stations are co-located and diplexed on a six-tower antenna array. Each was tested for all-digital and hybrid AM operation. Figure 24 and Figure 25 show the all-digital AM daytime and nighttime coverage for KKXA, respectively, and likewise Figure 26 and Figure 27, for KRKO. Note that the testing at these two stations was done sequentially and not simultaneously, although simultaneous operation did not appear to be an issue nor would it be expected to be, given the wide frequency separation (140 kHz). Hybrid AM maps are not included here but as was true at the other tested stations, the all-digital AM coverage proved to be of greater extent and significantly more robust than the hybrid AM coverage.

One of the test routes for these stations was the only one in the test project to include test vehicle transport on ferry boats. For the daytime routes only, there were three ferry boat rides on the west route: the Clinton-Mukilteo, Port Townsend-Coupeville, and Edmonds-Kingston ferries. AM reception on the ferries (either analog or all-digital) depended upon the location of the vehicle in the ferry boat. On one ferry trip, when the vehicle was at the very front of the boat, good all-digital AM reception was experienced. On the other ferry trips, there was either spotty or no AM reception.

The nighttime coverage observed for station KRKO deserves some discussion. The predicted analog NIF contour for this station was 2.4 mV/m (see Table 4) which is the lowest value for any of the stations tested and suggests that there is a relatively low amount of interference for this station at night, which should result in better relative nighttime coverage than stations with a higher NIF. The measured coverage as shown in Figure 27, however, indicates that on the north, northeast, and southwest test routes the all-digital POF occurred inside of the predicted NIF contour, and in fact these were the only test routes observed (for this or any station tested under this project) where this was the case. In considering this behavior, KRKO engineering staff suggested that for this station, the M3 predictions of groundwave coverage are unrealistic because the ground conductivity in this region is significantly lower than the ground conductivity indicated in the M3 conductivity map used as the basis for NIF contour predictions. [8] Their belief is that if it were possible to estimate the groundwave coverage based on actual ground conductivities then the observed POFs would have occurred outside of the true NIF for the station.

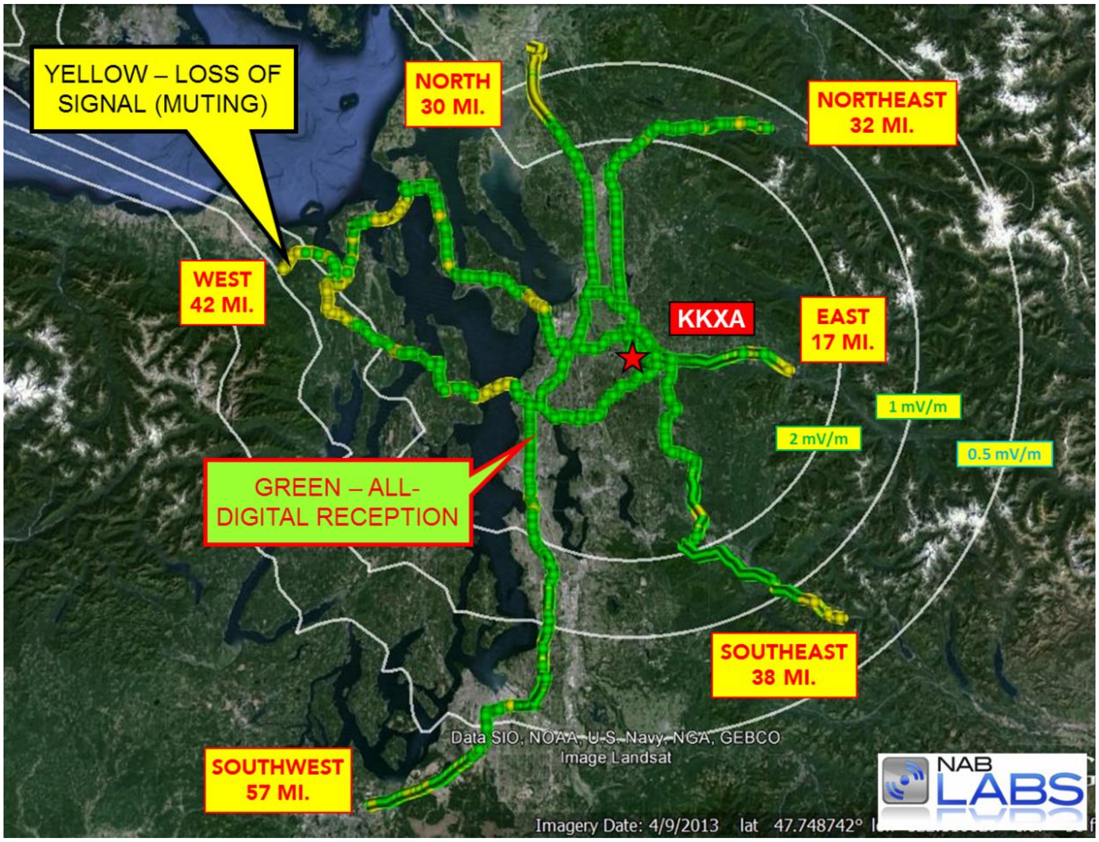



Figure 24. KKXA daytime all-digital AM coverage results (predicted analog contours shown)

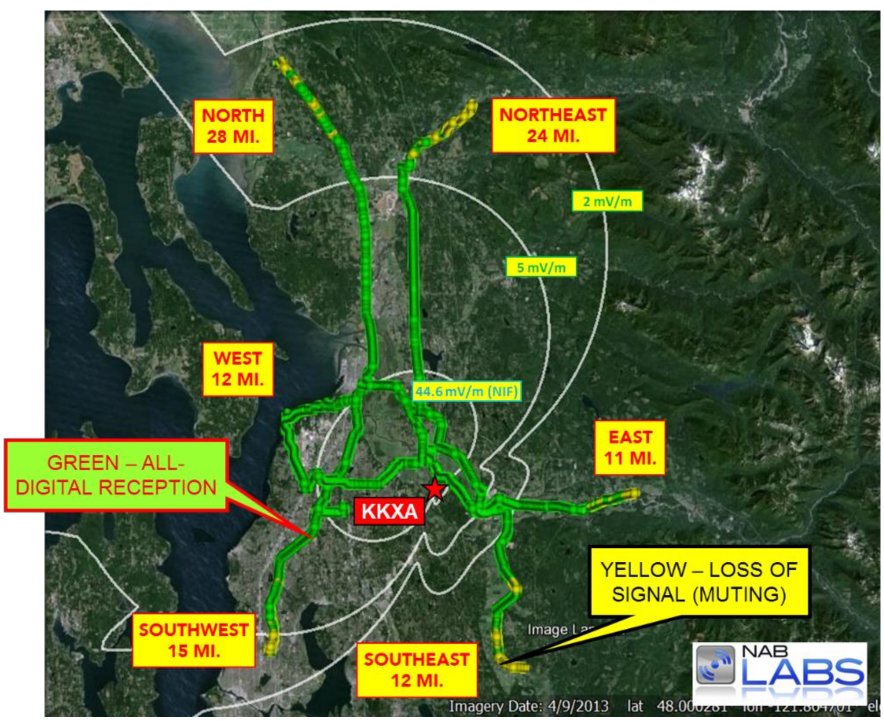



Figure 25. KKXA nighttime all-digital AM coverage results (predicted analog contours shown)

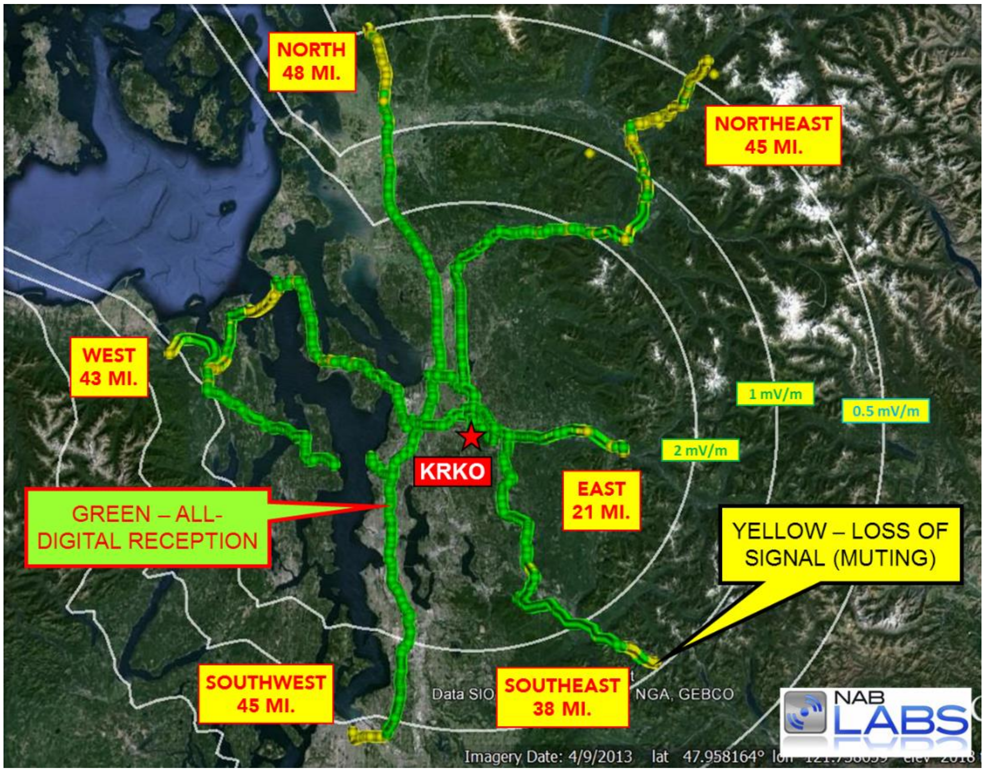



Figure 26. KRKO daytime all-digital AM coverage results (predicted analog contours shown)

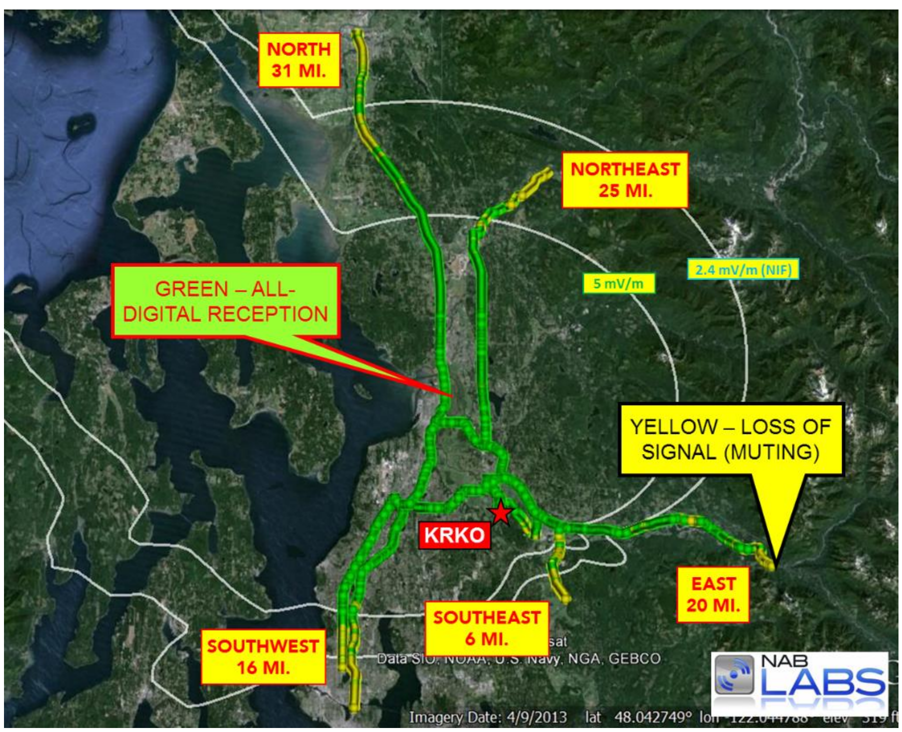



Figure 27. KRKO nighttime all-digital AM coverage results (predicted analog contours shown)

### Field Strength Measurements

As previously mentioned, numerous field strength measurements were made during the field tests described in this report. These measurements were typically made at or near the all-digital POF in an attempt to determine the field strength associated with loss of all-digital signal reception. In some cases, it was possible to briefly turn off the transmitter and/or switch from all-digital to analog transmission, allowing for field strength measurements of these other signal conditions to be made at the same location and at nearly the same time as the all-digital measurement. Measurements made with the transmitter turned off were especially interesting as they allowed for observation of the interfering field strength existing at the all-digital POF, and subsequent estimation of the desired-to-undesired (D/U) ratio at this point.

Two different measuring devices were used, both made by Potomac Instruments: the "classic" FIM-41 and the more modern PI-4100 (shown in Figure 28). Because these units have a limited bandwidth (less than the bandwidth of the signal being measured) and are calibrated for measurement of *analog* AM signals, when they are used to measure the field strength of an MA3 all-digital AM signal a correction factor must be applied to the observed value. Potomac Instruments recommends that a correction factor of 3.9 dB be added to MA3-mode measurements made in dBuV/m with the PI-4100 (corresponding to a multiplication factor of 1.567), which takes into account the 1 kHz measurement bandwidth of the PI-4100 and the MA3 signal structure. [9]

Some example field strength measurement results are provided in Table 5, for station KTUC (1400 kHz, Tucson, AZ), taken at the all-digital POF for the north and west test routes.[13] Using these measurements it was possible to calculate a desired-to-undesired (D/U) field strength ratio at the all-digital POF, shown in the last column of the table. Regarding these measurements:


Figure 28. Potomac Instrument field strength meters used for measuring field strength (photos courtesy Potomac Instruments)

- For each group (W night, N day, W day), the test vehicle was driven from the transmitter site along the prescribed route out to the all-digital POF as determined by loss of the 25-Hz audio tone, detected using the data collection system described above;
- At or near the all-digital POF, the vehicle was pulled off of the test route into a parking lot or other location where the driver could safely park and exit the vehicle to make field strength measurements (ideally, away from potential sources of RF interference or re-radiating structures);
- The driver contacted the station engineer (at the transmitter site) and arrange for switching of the signal from all-digital to analog and/or no carrier, and made field strength measurements for each case as appropriate (note that at some of the more remote sites where cellular telephone service was unavailable, specific times for switching of the transmit signal were pre-arranged). Care was taken to insure that the transmit power in both the analog and all-digital cases was equivalent;

Table 5. Field strength measurements of KTUC (1400 kHz, Tucson, AZ) taken at the all-digital AM point-of-failure (POF).

| | | | | FIELD STRENGTH (mV/m) | | COORDINATES | | CALCUATED |
|---|---|---|---|---|---|---|---|---|
| ROUTE | D/N | TIME | TYPE | MEASURED | CORRECTED | LAT | LONG | D/U AT POF (dB) |
| W | NIGHT | 20:40 | Digital | 9.550 | 14.965 | 32.175610 | -111.054397 | 29.56 |
| | | 20:42 | Analog | 14.000 | | | | |
| | | 20:46 | No carrier | 0.498 | | | | |
| N | DAY | 13:50 | Digital | 0.268 | 0.420 | 32.689998 | -111.080694 | 14.59 |
| | | 13:57 | No carrier | 0.078 | | | | |
| W | DAY | 16:18 | Digital | 0.175 | 0.274 | 32.034137 | -111.547863 | 16.57 |
| | | 16:20 | No carrier | 0.041 | | | | |
| | | 16:22 | Analog | 0.226 | | | | |

[13] All of the field strength measurements in Table 5 were made with the PI-4100 field strength meter.

- Upon completion of the field strength measurements, the all-digital signal would be restored and additional all-digital coverage measurements would be made.

A comparison of the analog and (corrected) digital field strength measurements in Table 5 (for W night and W day) serves as a check on the proper (and equivalent) power setting for each case: for W night, 14.965 (digital corrected) vs. 14.000 (analog) mV/m, and W day, 0.274 (digital corrected) vs. 0.226 (analog) mV/m.

There is also fairly good correlation between the calculated D/U at POF for the N day (14.59 dB) and W day (16.57 dB) routes. The W nighttime D/U calculation at POF (29.56 dB) is significantly higher than the daytime values and reflects the poorer all-digital system performance that was generally observed at night.

### Laboratory testing of the All-digital AM Signal

In addition to characterizing the real-world *coverage performance* of the all-digital AM signal (the principal goal of the field test portion of this project), it is also necessary to establish the *interference performance*, in particular with respect to co-, first-, and second-adjacent channel AM radio signals, since station allocation rules are based on this interference behavior. Interference performance testing of this type cannot be accomplished in the field because of the numerous and uncontrollable variables which exist there, and instead must be undertaken in a laboratory environment where proper controls may be exercised and variables may be isolated and/or eliminated.

The initial, exhaustive testing of the hybrid AM mode of operation done by iBiquity and submitted to the NRSC prior to the FCC's authorization of the hybrid mode of operation included a substantial amount of laboratory testing to characterize interference behavior. [10] Those test data were evaluated by the NRSC's Digital Audio Broadcasting (DAB) Subcommittee and figured prominently in the NRSC's endorsement of daytime hybrid AM operations. [11]

When comparing the hybrid and all-digital AM modes of operation with respect to co- and adjacent-channel interference performance a number of observations are apparent. By design, all-digital AM will cause significantly less interference to adjacent channel signals by virtue of its reduced RF bandwidth (either ±5 or ±10 kHz) compared to hybrid AM (with a bandwidth of ±15 kHz).[14] Consequently, it would appear that there is no need to conduct additional adjacent-channel interference tests on the all-digital AM signal since the exhaustive hybrid AM tests already conducted represent the worst-case adjacent-channel interference conditions for the HD Radio AM system.

On the other hand, co-channel interference from an all-digital AM signal will be greater than experienced from a hybrid AM signal since the digital sidebands immediately adjacent to the unmodulated carrier are significantly more powerful. Additional testing is in order for all-digital AM co-channel interference since there were no tests of this sort done in the earlier iBiquity tests. Co-channel interference from an all-digital AM signal will also be greater than that experienced from a co-channel analog AM signal since the power spectral density of an orthogonal frequency division multiplex (OFDM) digital waveform (in particular, that of the primary digital sidebands) is greater than that of an analog AM signal.[15]

To conduct lab interference testing of the all-digital AM signal, NAB Labs constructed a radio test bed capable of performing both co- and adjacent-channel testing into a number of test receivers. Figure 29 is a high-level block diagram showing some of the main components of the test bed and the RF signal flow; a photograph of the test bed is provided in Figure 30. Five different consumer receivers are being tested (Table 6).

Table 6. Receivers used in all-digital AM lab testing

| NO. | MFG. | MODEL | TYPE | HD RADIO-capable? |
|---|---|---|---|---|
| 1 | Insignia | ITR | Table top | YES |
| 2 | Delphi | 2B379649 | Automotive OEM | YES |
| 3 | Pioneer | DEH-X8600BH | Aftermarket automotive | YES |
| 4 | Kenwood | KDC-BT758HD | Aftermarket automotive | YES |
| 5 | Clarion | CZ102 | Aftermarket automotive | NO |

At the submission time for this paper, the co-channel interference testing was not completed and the final report on the NAB Labs all-digital AM lab testing had not been released, so a comprehensive discussion of the lab test effort and results is not included here. A brief summary of this activity, however, is provided:

- The lab test effort focuses on co-channel testing because of the reasons stated above. Briefly, the procedure being followed is to establish a variety of co-channel scenarios and then for each scenario, vary the desired-to-undesired (D/U) ratio and measure the resulting audio signal-to-noise ratio (SNR) for an analog AM desired signal, and the POF for an all-digital AM desired signal. Numerous audio recordings are being made as well, for possible future subjective evaluation. A lab test matrix is provided in Table 7.

[14] See Figure 5. One particularly attractive feature of the reduced bandwidth mode of all-digital AM is that it imparts essentially no interference to a first (or second)-adjacent channel neighbor.

[15] Co-channel interference was investigated in the field test portion of this project at station WSWW and is discussed above, see in particular Figure 23. The field observations at WSWW indicated that the impairment to analog co-channel stations was essentially equivalent irrespective of whether the interference from WSWW was from an analog or an all-digital AM signal.

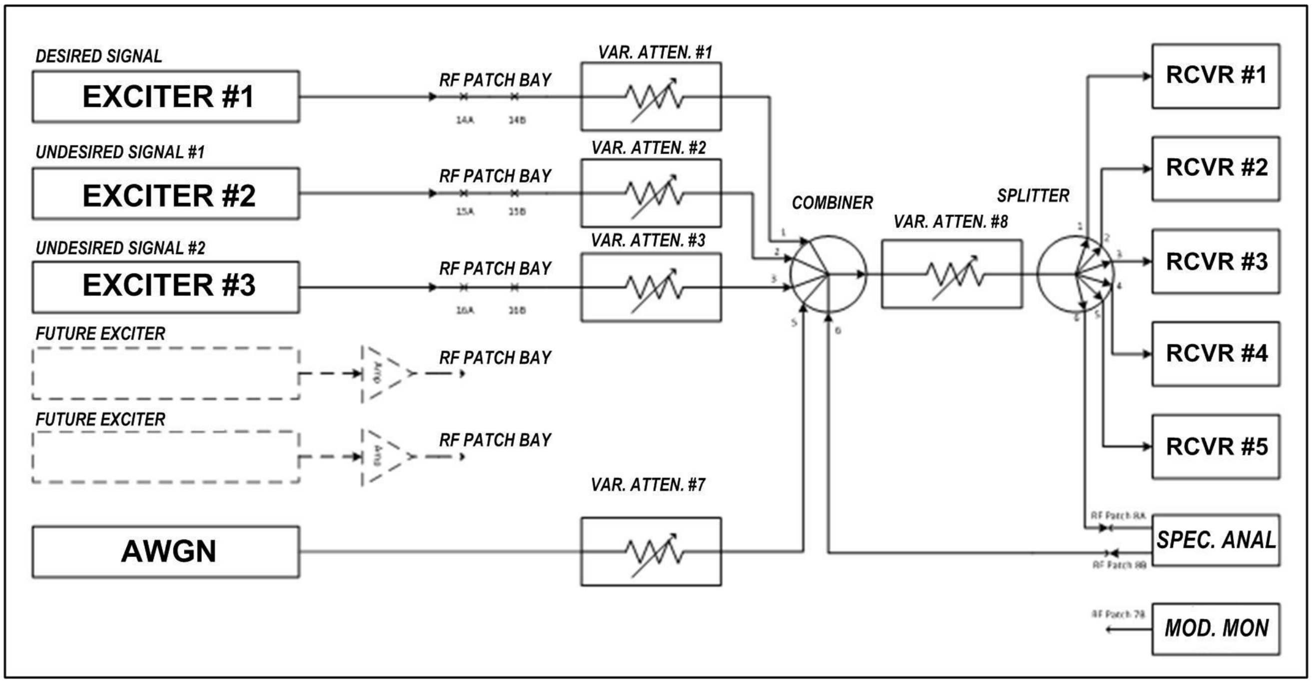



Figure 29. NAB Labs radio test bed RF signal flow block diagram

- One of the principal distinguishing features between test scenarios here is the phase/frequency relationship between the desired and undesired RF carriers. The first group of tests are being conducted with the desired and undesired carriers at the same frequency but with phase offsets of zero, ninety, and one hundred eighty degrees between them. These scenarios are representative of situations where co-channel stations are using transmitters that are locked to the same frequency reference, for example, a Global Positioning System (GPS) reference. For the second group of tests, frequency offsets of ±1, ±2, and ±5 Hz are being established between the desired and undesired carriers, representing the situation where these carriers are not at the same frequency.[16] In these situations, when two analog AM stations are co-channel to one another, a "beating" effect can be heard which is proportional to the amount of frequency difference between the carriers.

Figure 30. NAB Labs radio test bed

[16] The FCC rules state that for an AM station "The departure of the carrier frequency for monophonic transmissions or center frequency for stereophonic transmissions may not exceed ±20 Hz from the assigned frequency." 47 CFR §73.1545.

Table 7. All-digital AM lab test co-channel matrix

| Test No. | Undesired | Desired | Carrier phase offset (deg) | Freq. offset (Hz) | Audio recordings |
|---|---|---|---|---|---|
| 1 | Analog | Analog | 0 | 0 | |
| 2 | All-digital | | | | |
| 3 | Analog | All-digital | | | |
| 4 | All-digital | | | | |
| 5 | Analog | Analog | 90 | 0 | |
| 6 | All-digital | | | | |
| 7 | Analog | All-digital | | | |
| 8 | All-digital | | | | |
| 9 | Analog | Analog | 180 | 0 | |
| 10 | All-digital | | | | |
| 11 | Analog | All-digital | | | |
| 12 | All-digital | | | | |
| 13 | Analog | Analog | - | +1 | ✓ |
| 14 | All-digital | | | | ✓ |
| 15 | Analog | All-digital | | | |
| 16 | All-digital | | | | |
| 17 | Analog | Analog | - | +2 | ✓ |
| 18 | All-digital | | | | ✓ |
| 19 | Analog | All-digital | | | |
| 20 | All-digital | | | | |
| 21 | Analog | Analog | - | +5 | ✓ |
| 22 | All-digital | | | | ✓ |
| 23 | Analog | All-digital | | | |
| 24 | All-digital | | | | |
| 25 | Analog | Analog | - | -1 | ✓ |
| 26 | All-digital | | | | |
| 27 | Analog | All-digital | | | |
| 28 | All-digital | | | | |
| 29 | Analog | Analog | - | -2 | |
| 30 | All-digital | | | | |
| 31 | Analog | All-digital | | | |
| 32 | All-digital | | | | |
| 33 | Analog | Analog | - | -5 | |
| 34 | All-digital | | | | |
| 35 | Analog | All-digital | | | |
| 36 | All-digital | | | | |

## Summary and Future Activities

With this project, NAB Labs is significantly expanding the knowledge and understanding of the all-digital AM system. Field test results have characterized the coverage performance for a variety of station types using readily-available consumer radio receivers. Lab test results will provide information on the co-channel interference behavior of the all-digital AM signal into both analog and all-digital desired signals.

A possible future all-digital AM-related testing and study activity pertains to RF mask compliance. As briefly mentioned earlier, the observed level of compliance with the MA3 RF mask specified in NRSC-5 at the field test stations varied. This mask was specified by iBiquity prior to the widespread development and deployment of AM HD Radio transmission equipment and is likely to be re-evaluated to take into account operational information and an assessment of the realizable performance of AM facilities.

## Acknowledgments

NAB Labs gratefully acknowledges the participation of numerous individuals and organizations in the planning and execution of the tests described in this report. A number of broadcast consulting engineers made significant contributions to this work including Dan Ryson and Mike Rhodes with Cavell, Mertz & Associates, and Dennis Wallace with MSW, LLC. Special recognition is due to the broadcasters, consultants and equipment manufacturers who made their stations and support personnel available at the field test sites, including the following (apologies to anyone overlooked!):

*Beasley Broadcast Group* – Mike Cooney, Richard Banks
*Broadcast Electronics* – Tim Bealor, Brent Whelan
*CBS Radio* – E. Glynn Walden, Alan Lane, Tom McGinley
*Cumulus Media* – Gary Kline, Mark Simpson, Martin Stabbert, Ron Bedoya
*GatesAir* – Tim Anderson, Terry Cockerill, Kevin Haider
*Greater Media* – Milford Smith, Jerry Dowd
*Hatfield & Dawson* – Stephen Lockwood, Jim Hatfield
*Hubbard Broadcasting* – Dave Garner
*iBiquity Digital Corporation* – Ashruf El-Dinary, Russ Mundschenk, Harvey Chalmers, Mike Raide, Brian Kroeger
*Kintronic Labs* – Tom King, Josh King
*Nautel* – Jeff Welton, Gary Liebisch, Phillip Schmid, Tim Hardy
*Potomac Instruments* – Guy Berry, Cliff Hall
*S-R Broadcasting* – Andy Skotdal, Buzz Anderson
*West Virginia Radio Corporation* – Dale Miller, Chris Moran, Noel Richardson
*WRPX, Inc*. – Greg Borgen, Mark Mueller

## References


[1] FCC, *In the Matter of Digital Audio Broadcasting Systems and Their Impact on the Terrestrial Radio Broadcast Service, First Report and Order*, Adopted October 10, 2002, MM Docket No. 99-325, FCC 02-286

[2] *NRSC-5-C, IBOC Digital Radio Broadcasting Standard*, National Radio Systems Committee, September 2011 (first adopted April 2005)

[3] *HD Radio Adoption by Consumers in 2014 Contributes to Nearly 25 Million Units in Use, Driving New Content Offerings from Broadcasters and High Satisfaction*, iBiquity Press Release, January 5, 2015

[4] *AM All-digital IBOC Field Test Report*, iBiquity Digital Corporation, April 12, 2002

[5] Layer, David H., et. al., *WBCN All-digital AM IBOC Field Test Project*, 2013 NAB Broadcast Engineering Conference Proceedings, April 2013, pp. 183-193

[6] *HD Radio Air Interface Design Description Layer 1 AM*, iBiquity Digital Corporation, Doc. 1012s, Rev. F, August 23, 2011

[7] *HD Radio AM Transmission System Specification*, iBiquity Digital Corporation, Doc. 1082s, Rev. F, August 24, 2011

[8] M3 Map of Effective Ground Conductivity in the United States, 47 CFR §73.190,

[9] Hall, Cliff, *PI 4100 Field Strength Correction for HD Radio All-Digital MA3 Mode*, Private communication from Potomac Instruments to NAB Labs, June 21, 2013

[10] *AM IBOC DAB Laboratory and Field Testing: Third Report to the National Radio Systems Committee*, iBiquity Digital Corporation, January 4, 2002

[11] *Evaluation of the iBiquity Digital Corporation IBOC System - Part 2- AM IBOC*, National Radio Systems Committee, April 6, 2002

# NAB Labs All-digital AM Test Project - Part II, Co-channel Laboratory Test Results

David H. Layer
National Association of Broadcasters
Washington, DC

Michael D. Rhodes
Cavell, Mertz & Associates
Manassas, VA

Daniel G. Ryson
Cavell, Mertz & Associates
Manassas, VA

**Abstract –** *Since 2012, NAB Labs has been conducting field and laboratory tests of the HD Radio all-digital AM system. The purpose of this test project has been to characterize the digital coverage performance and interference behavior of the all-digital AM signal under a variety of conditions, with the goals of better understanding the capabilities and limitations of this signal and to develop a technical record of this as-yet unauthorized service. This paper, the second in a series, focuses on the laboratory interference testing portion of the project including a summary of the co-channel laboratory test results obtained by NAB Labs.*

## Introduction

The National Association of Broadcasters, through its NAB Labs initiative,[1] performed a series of laboratory tests on all-digital AM signals using the HD Radio digital radio system. The purpose of these tests was to characterize the co-channel interference behavior of the HD Radio all-digital AM system.[2]

The laboratory test plan for these tests is based in part upon the National Radio Systems Committee's (NRSC's) AM band IBOC laboratory test procedures, developed in 2002 as part of the laboratory test program conducted on the HD Radio hybrid AM system.[2] That test program and subsequent test results were thoroughly evaluated by the NRSC's Digital Audio Broadcasting (DAB) Subcommittee.[3] This NRSC evaluation was submitted to the FCC and was instrumental in the FCC's adoption of hybrid IBOC as the U.S. digital radio standard.

Laboratory testing is ideally suited for characterizing differences between various receivers and differences in modulation schemes. As detailed below, the laboratory environment permits measurements under consistent signal propagation conditions, a necessity for repeatable results. The tests detailed in this report are grouped into "Phase 1" and "Phase 2," where the Phase 1 tests are intended to simulate ideal (noise-free) conditions, and Phase 2 tests are intended to simulate "real world" (noisy) reception environments.

## Test bed description

During these tests, the NAB Labs test bed was located in the Manassas, VA facilities of the broadcast engineering firm of Cavell, Mertz & Associates. It consists of two equipment racks (an RF equipment rack and an audio equipment rack) and some associated peripheral equipment. The RF equipment rack contains the RF equipment including exciters, exporters, combiner, splitter, attenuators, RF patch panel, RF noise generator, spectrum analyzer and the test receivers. The system's UPS and receiver 12V power supply are also mounted in this rack.

The audio equipment rack contains the audio router, audio test and measurement equipment, automation and control computer, audio processors, and audio noise generator. Both racks incorporate grounding bars with all equipment chassis directly connected to the ground bars and the ground bars are connected to the system common power supply ground. All power to the test bed is supplied through the UPS.

The diagrams and pictures below serve to further document and describe the test bed. Figure 1 shows the test bed RF signal flow, while Figure 2 illustrates the audio signal flow. Figure 3 and Figure 4 show the equipment rack layouts for the RF and audio portions of the system, respectively.

Preliminary testing was conducted using a carrier frequency of 1000 kHz, in the middle of the AM broadcast band. However, a low level spurious emission from the exciters was discovered within 30 kHz of the 1000 kHz carrier frequency. Changing the carrier frequency caused the spur to change frequency non-linearly with respect to the carrier. In a desire to avoid this spur when testing adjacent channels, it was determined that the nearest carrier frequency on which this spur would not be a factor was 890 kHz. Therefore all testing herein was performed at a carrier frequency of 890 kHz.

This spur was discussed with the exciter manufacturer engineers and it was determined that the spur is only on the RF monitor output of the exciter that is being used for these tests. The spur would not be present on the magnitude/phase outputs that would typically be connected to a transmitter. It was further verified with the manufacturer that the RF monitor output is otherwise acceptable for performing the interference tests described in this paper.

[1] NAB Labs is now part of NAB's PILOT initiative.

[2] See [1] for information on the field test portion of this NAB Labs all-digital AM project, as well as for additional background information on the all-digital AM system.

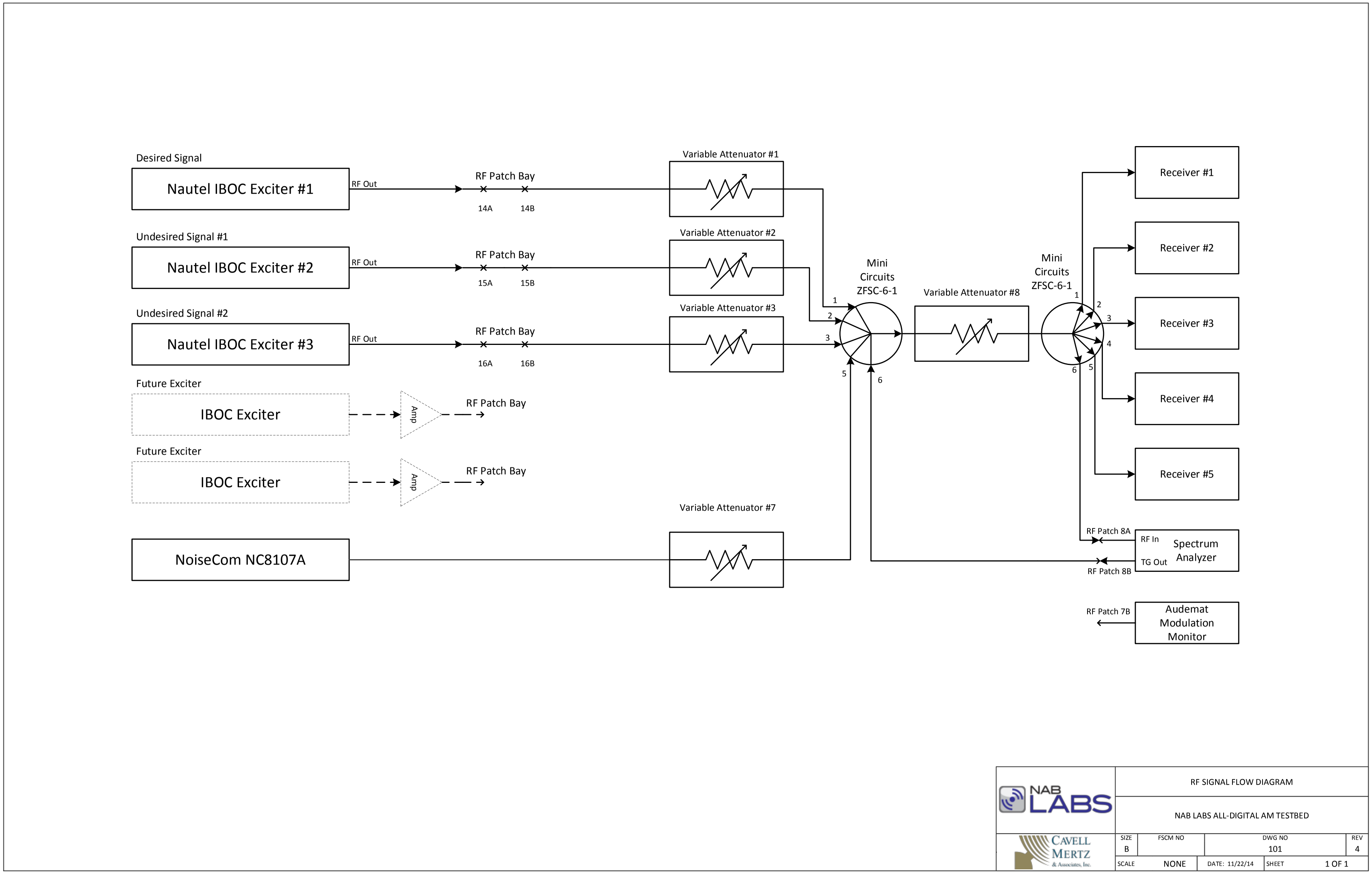



Figure 1. Test bed RF signal flow diagram

PREVIOUS VIEW

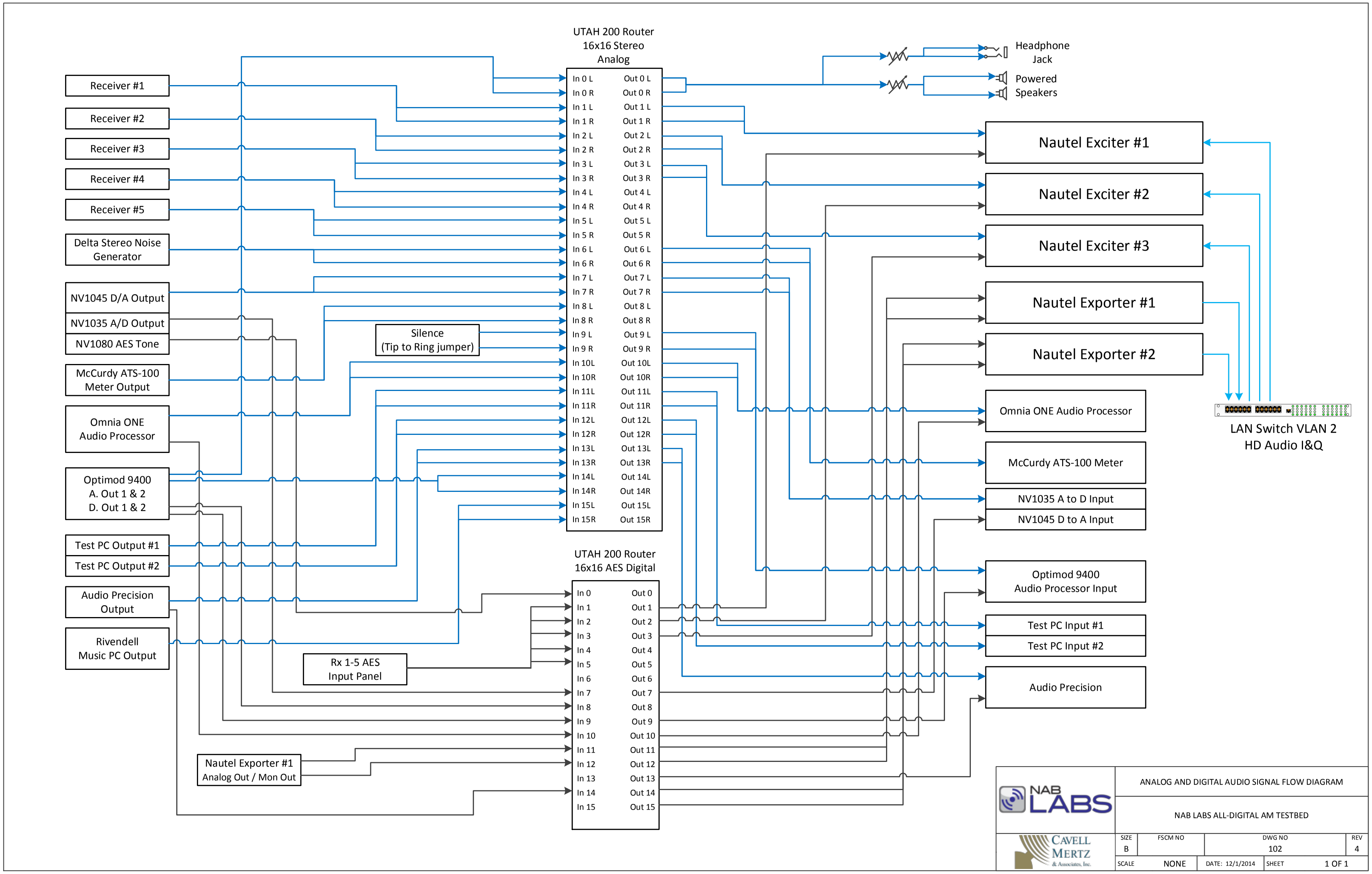



Figure 2. Test bed audio signal flow diagram

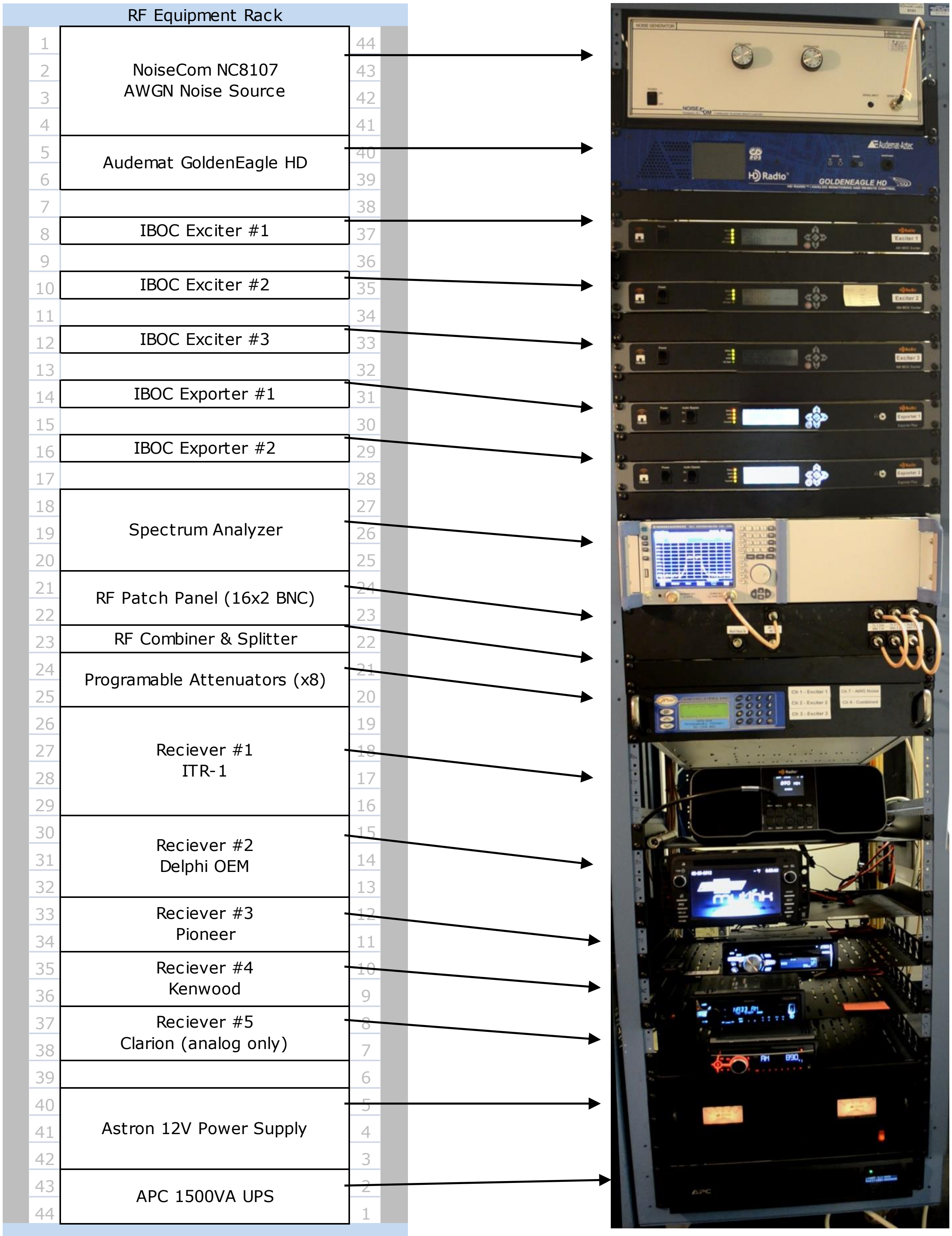



Figure 3. Equipment rack layout – RF rack

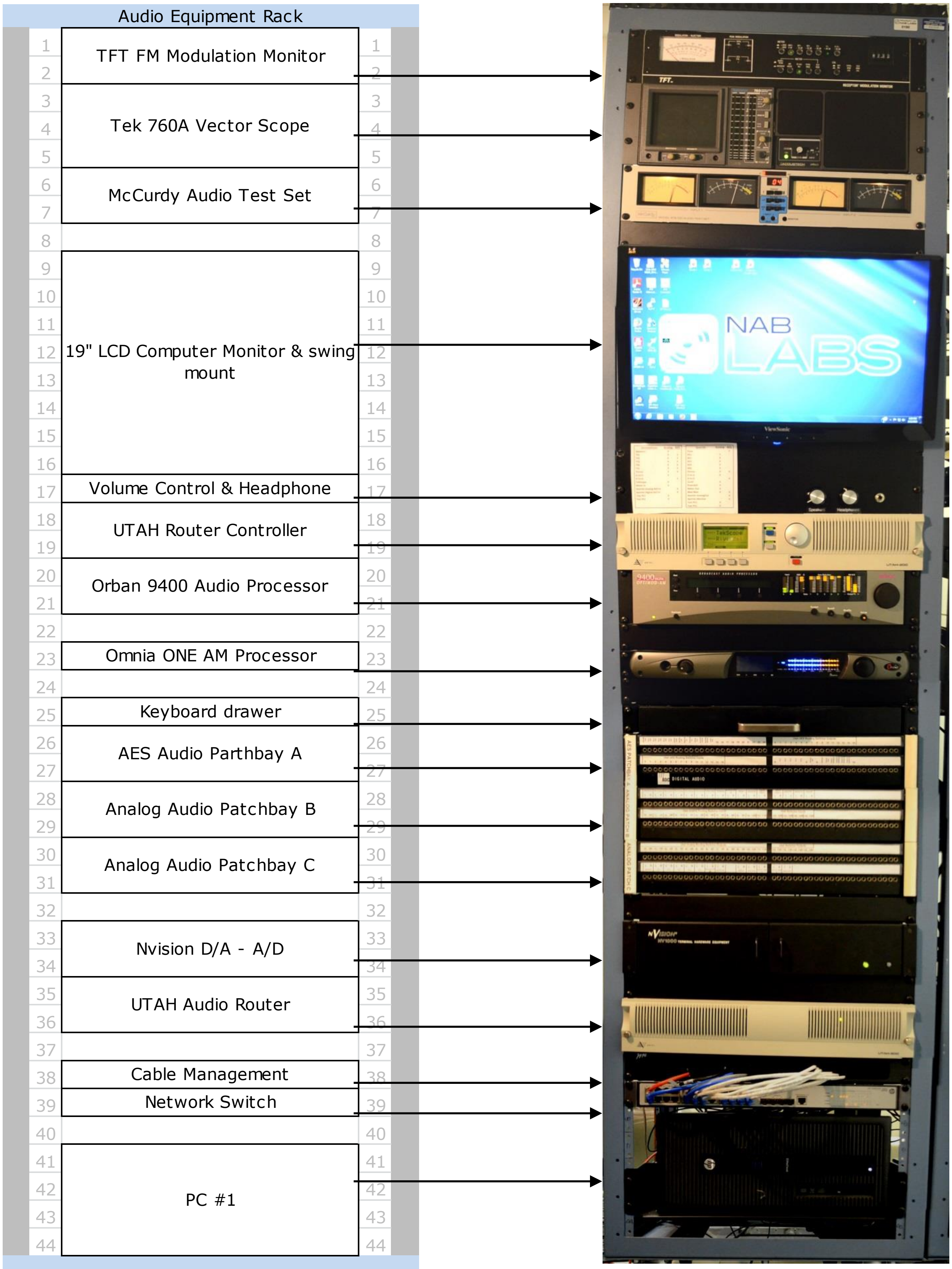



Figure 4. Equipment rack layout – audio rack

## Receivers

The HD Radio test receivers were chosen based on a variety of factors. First, the Insignia ITR was the only table top HD Radio receiver currently available. An original equipment manufacturer (OEM) radio was obtained from Delphi Automotive PLC.[3] Delphi is a leading global supplier of technologies for the automotive and commercial vehicle markets and designs and manufacturers radios used in General Motors and other vehicles.

Several aftermarket radios were also utilized. Two aftermarket HD Radio receivers were selected from different manufacturers. These are considered to be mid-priced receivers. Since there are a limited number of manufacturers of receiver tuner and HD Radio decoder chip sets, the chosen radios were vetted by iBiquity personnel to assure there was no duplication of tuner and/or decoder chipsets. These receivers were purchased from a national consumer electronics vendor.

Finally, the tests performed herein are designed to determine the impact of HD Radio signals on analog reception. Since HD Radio-capable receivers may have different analog tuner characteristics from analog-only receivers, an analog-only radio was selected as the fifth receiver for use in the analog tests. A low priced, analog-only radio from a third manufacturer was selected and sourced from the same consumer electronics vendor used in procuring the HD Radio receivers.

During the initial evaluation of these receivers it was determined that several had the capability to turn off the HD Radio digital signal reception or to force the radio to only receive analog or HD Radio digital signals by changing menu settings in the radio.

Specifically, the Delphi has "HD enable/HD disable" modes of operation. When in HD disable mode, only analog signals are received regardless of the presence of an HD Radio digital signal. The Kenwood radio has a similar menu setting of "Digital/Analog/Both," however, it was found that even when set to Analog mode, when a digital interferer was present at a sufficient level this receiver would mute the audio entirely, thus turning off an otherwise listenable analog station. The results of tests in each mode for both of these receivers can be found in Appendix 2.

A table of the test receivers and pictures of the receiver front panels are given in Table 1 and Figure 5, respectively. These are pictures of the receivers as installed and operating in the test bed.


Figure 5. Test receivers

## Receiver connections

Receiver connections to the test bed were made using the same methodology used by iBiquity in their test lab. The four automotive receivers were connected using a "Motorola" type connector to BNC adapter connected in parallel with a 50Ω load using a BNC "tee" as shown in the diagram and photo in Figure 6.

[3] Delphi Automotive also supplied a "keep alive" or "saint" box that is connected to the radio and mimics the automotive data network, allowing the OEM radio to operate outside of a vehicle.

Table 1. Test receivers

| No. | MANUFACTURER | MODEL | TYPE |
|---|---|---|---|
| 1 | Insignia | ITR | Table top |
| 2 | Delphi | 2B379649 | OEM Auto HD & Analog |
| 3 | Pioneer | DEH-X8600BH | Aftermarket Auto HD & Analog |
| 4 | Kenwood | KDC-BT758HD | Aftermarket Auto HD & Analog |
| 5 | Clarion | CZ102 | Aftermarket Auto Analog Only |

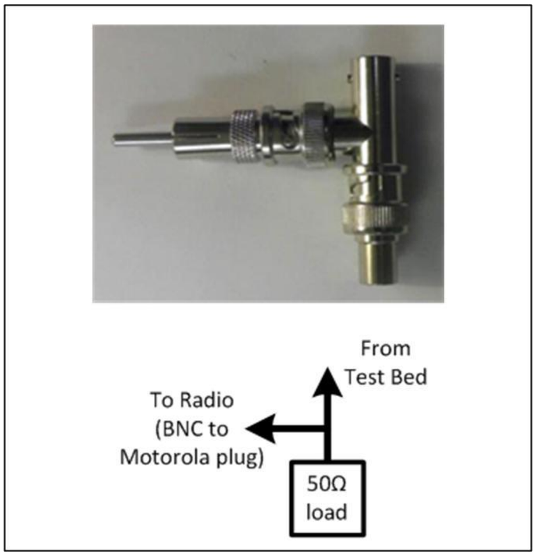



Figure 6. Automotive receiver RF signal interface

The Insignia table top receiver's AM antenna is connected using a 3.5 mm two-conductor plug designed to accept the connection from the stock loop antenna (provided with the receiver). A 3.5 mm to BNC adapter was used at the radio. iBiquity engineers familiar with this radio recommended that an 11 μH inductance be placed in series to simulate a stock loop antenna. A metal box was fabricated to provide BNC connections to this series 11 μH inductor. This inductor was terminated into a 50 Ω load on the test bed end using a BNC tee. A diagram and photo of this connection is shown in Figure 7.

All power measurements were made using the test bed spectrum analyzer's 50 Ω input. As shown in Figure 1, the signal is evenly divided between the six outputs of the Mini-Circuits divider, thus the same signal is presented to each receiver's connection network as is measured by the spectrum analyzer.

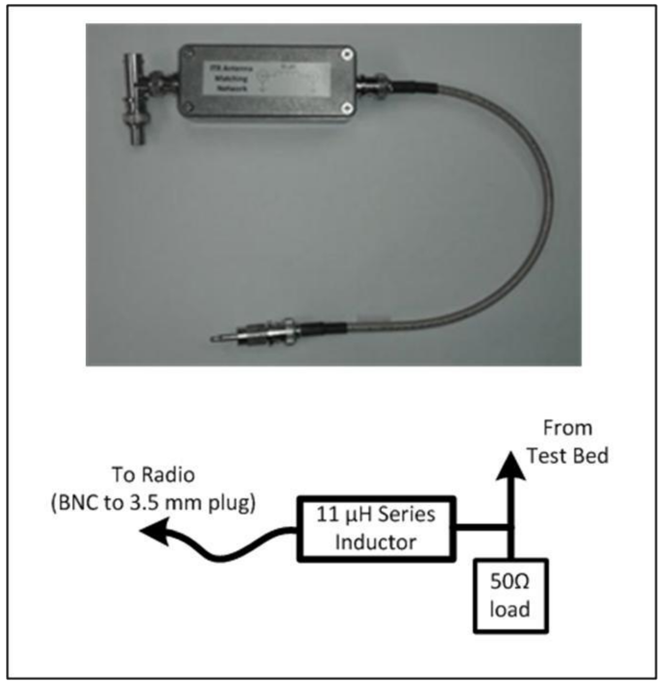



Figure 7. Insignia receiver RF signal interface

Using the receiver connections just described, the receiver input impedances were measured with a network analyzer. These measurements were made at the point where the cable from the Mini Circuits splitter is connected to the BNC tee. The input impedance for each receiver (both with and without the 50 Ω tee) is provided in Table 2.

### All-digital threshold of reception

For calibration and testing purposes, the threshold of all-digital reception was used as a repeatable measurement of test bed and receiver performance.

Table 2. AM test receiver input impedances at 890 kHz

| No. | MANUFACTURER | MODEL | MEASURED INPUT IMPEDANCE (AT RADIO INPUT), Ω | MEASURED INPUT IMPEDANCE (RADIO WITH 50 Ω TEE) , Ω |
|---|---|---|---|---|
| 1 | Insignia | ITR | 54.1 – j7.8 | 29.9 + j8.2 |
| 2 | Delphi | 2B379649 | 10.8 – j532.1 | 49.7 – j4.7 |
| 3 | Pioneer | DEH-X8600BH | 1104.1 – j1354.3 | 50.4 – j1.2 |
| 4 | Kenwood | KDC-BT758HD | 12.2 – j 775.8 | 50.2 – j3.3 |
| 5 | Clarion | CZ102 | 20.5 – j307.7 | 48.6 – j7.9 |

A series of tests were performed on each receiver to determine the minimum RF power level at which no impairments could be heard. The all-digital signal was reduced in 1 dB steps until impairments were heard over a 10 second period. The digital RF channel power was measured over a 30 kHz bandwidth. The last measured RF level at which no impairments are heard is given in Table 3. All-digital threshold of reception tests along with the analog signal-to-noise tests with no interferer served to verify proper test bed performance.

Table 3. AM test receiver threshold of digital reception

| No. | MANUFACTURER | MODEL | SIGNAL LEVEL (dBm) |
|---|---|---|---|
| 1 | Insignia | ITR | -110.9 |
| 2 | Delphi | 2B379649 | -107.2 |
| 3 | Pioneer | DEH-X8600BH | -105.0 |
| 4 | Kenwood | KDC-BT758HD | -108.3 |
| 5 | Clarion | CZ102 | (analog only) |

### Test bed noise floor evaluation

The initial design of the test bed included shielded enclosures for all receivers. Upon construction of the test bed it was found that there was minimal RF noise in the test lab and shielded enclosures would not be required. Measurements of the RF output of the test bed with all receivers connected and operating (see Figure 8) shows an acceptable noise floor. Average signal levels across the band (blue trace in Figure 8) are less than -125 dBm. The only signal ingress in the AM band is from a local broadcast station operating on 1460 kHz and located some 2.75 mi distant.

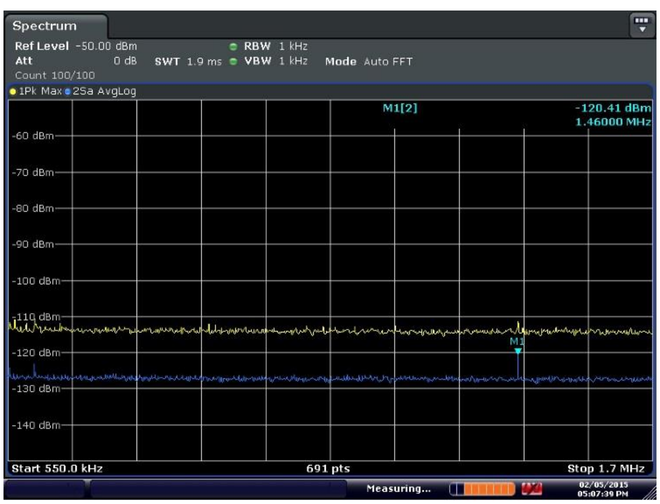



Figure 8. Spectrum analyzer plot showing RF output of test bed with all receivers connected and operating

Some limited receiver testing was done using an RF screen cage, to see if there was any change in performance compared to using no screen cage. Selected receivers were removed from the test bed and installed in the screen cage (see Figure 9). The cage was equipped with RF filtering on the AC power receptacles and audio cables as well as feed-through RF coax connections. The AC power for the screen cage was connected to test bed AC power supplied by the UPS. The digital signal threshold of reception with the receiver in the screen cage was found to be within 1 dB of those measurements shown in Table 3.

The screen cage testing was performed only for the purpose of verifying the test bed operation. All desired to undesired signal testing was done with the receivers mounted in the test bed rack as shown in Figure 3.

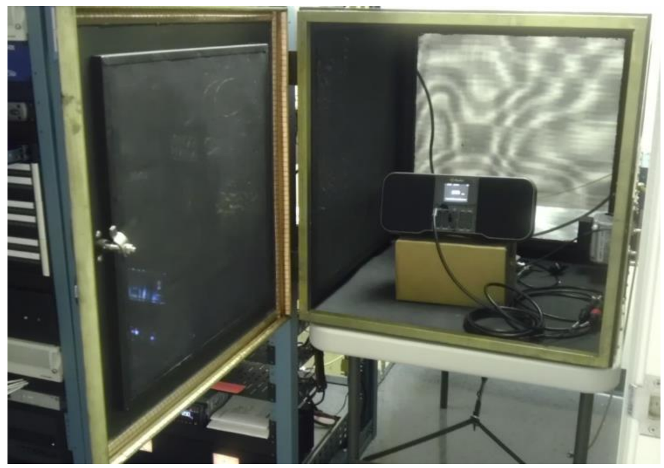


Figure 9. Screen cage test setup

### Establishing RF signal levels for testing

A review of prior AM IBOC laboratory measurement reports suggested that there had been challenges establishing appropriate RF reference power levels for testing purposes. Discussions with engineers involved in prior tests revealed that difficulties stemmed from wide variations among receiver antenna input impedances/reactances as well as significant disparities between efficiencies of various automobile antenna systems. As discussed above, substantial variations in receiver input characteristics were also observed in the NAB Labs test receivers, which are believed to be typical of the industry. It was therefore concluded that the laboratory 50 Ω signal level measurement power levels could at best only approximate free-space field strengths.

To provide some level of continuity between this effort and prior tests, Phase 1 (no AWGN) tests herein utilized the same three RF reference signal power levels that had been

used historically by others.[4] The reference 50 Ω signal levels used in Phase 1 were -48 dBm (“strong”); -62 dBm (“moderate”) and -76 dBm (“weak”).

When developing the test procedure for the Phase 2 AWGN tests, these tests focused on audio signal-to-noise measurements in cases of co-channel interference. In the FCC allocations methodology, co-channel interference typically, but not always, occurs only at weaker desired field strengths. Thus, for AWGN series of tests, the reference test levels were adjusted to approximate the FCC’s 0.5 mV/m; 2 mV/m; and 5 mV/m field strength standards that are used to define bounds of interference protection and coverage. Because the 76 dBm “weak” signal level already approximated the signal level at the 0.5 mV/m protected coverage contour, this reference level was retained.

For Phase 2 testing with added AWGN, these desired signal levels were used: -76 dBm (used as an approximation to 0.5 mV/m, also the same as the “weak” signal level used in Phase 1), -64 dBm (~ 2 mV/m or 12 dB higher than 0.5 mV/m) and -56 dBm (~5 mV/m, 8 dB higher than 2 mV/m).

## Test plan and procedures

Table 4 and Table 5 contain the test matrices for the Phase 1 and Phase 2 tests, respectively. The test numbers shown in these tables (first column) are referred to throughout the remainder of this paper.

Test procedures followed for these laboratory tests are detailed in Appendix 1. Phase 1 tests were performed for both analog and digital desired signals in an RF noise-free environment. No additional noise was added to simulate RF noise levels known to exist in “real world” receiving scenarios.

Table 4. Phase 1 test matrix. Shaded test numbers indicate test conditions for which audio recordings were made.

| Test No. | UNDESIRED | DESIRED | TEST CONDITIONS |
|---|---|---|---|
| 1 | Analog | Analog | Carrier Δϕ 0°<br>Carrier Δf 0 Hz |
| 2 | All-digital | | |
| 3 | Analog | All-digital | |
| 4 | All-digital | | |
| 5 | Analog | Analog | Carrier Δϕ 90°<br>Carrier Δf 0 Hz |
| 6 | All-digital | | |
| 7 | Analog | All-digital | |
| 8 | All-digital | | |
| 9 | Analog | Analog | Carrier Δϕ 180°<br>Carrier Δf 0 Hz |
| 10 | All-digital | | |
| 11 | Analog | All-digital | |
| 12 | All-digital | | |
| 13 | Analog | Analog | Carrier Δϕ n/a<br>Carrier Δf +1 Hz |
| 14 | All-digital | | |
| 15 | Analog | All-digital | |
| 16 | All-digital | | |

Table 4 (continued). Phase 1 test matrix

| Test No. | UNDESIRED | DESIRED | TEST CONDITIONS |
|---|---|---|---|
| 17 | Analog | Analog | Carrier Δϕ n/a<br>Carrier Δf +2 Hz |
| 18 | All-digital | | |
| 19 | Analog | All-digital | |
| 20 | All-digital | | |
| 21 | Analog | Analog | Carrier Δϕ n/a<br>Carrier Δf +5 Hz |
| 22 | All-digital | | |
| 23 | Analog | All-digital | |
| 24 | All-digital | | |
| 25 | Analog | Analog | Carrier Δϕ n/a<br>Carrier Δf -1 Hz |
| 26 | All-digital | | |
| 27 | Analog | All-digital | |
| 28 | All-digital | | |
| 29 | Analog | Analog | Carrier Δϕ n/a<br>Carrier Δf -2 Hz |
| 30 | All-digital | | |
| 31 | Analog | All-digital | |
| 32 | All-digital | | |
| 33 | Analog | Analog | Carrier Δϕ n/a<br>Carrier Δf -5 Hz |
| 34 | All-digital | | |
| 35 | Analog | All-digital | |
| 36 | All-digital | | |

Table 5. Phase 2 test matrix. Shaded test numbers indicate test conditions for which audio recordings were made.

| Test No. | UNDESIRED | DESIRED | TEST CONDITIONS |
|---|---|---|---|
| 13-2 | Analog | Analog | Carrier Δϕ n/a<br>Carrier Δf +1 Hz |
| 14-2 | All-digital | | |

For both Phase 1 and Phase 2 tests, interfering (“undesired”) signals of varying D/U ratios were established and audio SNRs for the analog desired signal were measured. The SNR measurement was repeated at decreasing D/U values from 70 dB to 0 dB (increasing levels of undesired signal), for the three RF levels used for the test (-48, -62, and -76 dBm for Phase 1; -56, -64 and -76 dBm for Phase 2). For the Phase 1 digital desired signal cases, RF interfering signal level was increased until the threshold of (desired) digital signal audio interference was reached.

Phase 2 tests were conducted with only analog desired signals since the focus of Phase 2 was the impact of all-digital interference on co-channel analog signals in a “real world” environment. For Phase 2, AWGN was combined with the desired and undesired RF signals to simulate environmental noise. Deciding how much noise to add proved challenging since no definitive studies have been performed that would give the precise amount of added RF noise which exists in the AM band. From experience, this noise level varies

[4] Specifically, the original laboratory tests conducted on the HD Radio system as described in [2].

dramatically depending on the location and environment. In order to determine the effect of added environmental RF noise, it was decided that an audio signal to noise ratio (SNR) of 45 dB would be used to represent a typical SNR at a station's 5 mV/m contour.

Using 45 dB SNR as a starting point, co-channel interference tests 13-2 and 14-2 (see Table 5) were conducted with an additive white Gaussian noise ("AWGN") RF noise generator connected in parallel with the desired and undesired RF test signals. The location of the noise generator is shown in Figure 1. The amplitude of the AWGN signal was adjusted using the available 1 dB increment attenuators to provide a ~45 dB audio SNR at each receiver output at a desired signal level of -56 dBm (which, for the purposes of these tests was assumed to approximate the 5 mV/m station contour). The tests were then repeated at desired signal levels of -64 dBm (approximating the 2 mV/m contour) and at -76 dBm (approximating the 0.5 mV/m contour) without changing the AWGN noise level.

Audio recordings were made of the received signals using all 5 receivers. For each receiver, recordings using the 2 minute test audio track were made with no impairment (Phase 1), AWGN noise at 45 dB SNR (with no undesired signal present), and the digital undesired signal plus noise. Recordings were also made with the analog undesired signal plus noise using the 6 minute audio track with all combinations of audio samples as desired and undesired audio. A summary of recordings is provided in Appendix 3. These recordings were collected for subjective evaluation by expert listeners, with the goal of assessing differences between audio quality when digital versus analog interferers were present.

As detailed in the test procedures in Appendix 1, each series of tests involved repeating the same test with slight changes to input signal parameters between each test. The automation features of the Audio Precision software were used to make and record the various measurements. A custom program was written to allow the Audio Precision to control the JFW step attenuators which varied the desired and undesired signal levels for each test. The results of the tests were then recorded by the Audio Precision software in both .pdf and .csv file formats for later analysis and incorporation into the results tables provided below. Automation was not able to control the audio router or exciters, so each test was started manually for each receiver.

Whenever appropriate, automation was utilized to assure that all receivers were exposed to identical test signals and procedures. This was found to be particularly useful for the analog desired tests where signal-to-noise measurements were performed at 10 dB desired-to-undesired ("D/U") ratios and 3 signal levels for each of the 5 receivers. However, automation was found to be inappropriate for testing digital desired signals, where the threshold of interference was best determined by operators listening for drop-outs in the desired digital signals.

Prior to any automated testing, signals for the desired and undesired signal sources were manually adjusted, calibrated, and verified pursuant to the test procedures detailed in Appendix 1. A single, manual signal-to-noise test was conducted with the receiver under test and compared with a baseline measurement to verify proper operation of the receiver and test bed equipment.

Following initial adjustments of the RF and audio signal parameters, the automation took care of changing RF and audio input parameters from one undesired signal level to the next. The Audio Precision equipment was also used to both play and record the uncompressed .wav file audio samples for later demonstration.

Here is a procedure typical of testing a desired analog signal with an undesired digital signal modulated with a 500 Hz tone:

1) Set RF output (desired and undesired) attenuator to 36 dB (strong signal level).
2) Set desired RF attenuator for 0 dB.
3) Set undesired RF attenuator for 127 (max) dB.
4) Wait 10 seconds. This gives the receiver time to switch to digital mode if enabled.
5) Generate silence at input of analog (desired) modulator.
6) Measure audio noise level, averaged over 10 seconds.
7) Generate a 1 kHz tone at -1 dBFS (99% modulation) at input of analog (desired) modulator.
8) Measure audio signal level, averaged over 10 seconds.
9) Calculate and save audio signal-to-noise ratio.
10) Generate a 1 kHz tone at -1 dBFS (99% modulation) at input of analog (desired) modulator.
11) Measure and save audio frequency – reception of 1 kHz indicates analog reception and 500 Hz indicates digital reception.
12) Set undesired RF attenuator for 70 dB. Repeat steps 4 – 11.
13) Set undesired RF attenuator. Repeat steps 4 – 11 at each D/U level: 60 dB, 50 dB, 40 dB, 30 dB, 26 dB, 20 dB, 10 dB, 0 dB.
14) Set RF output (desired and undesired) attenuator to 50 dB (moderate signal level).
15) Repeat steps 2 – 13.
16) Set RF output (desired and undesired) attenuator to 64 dB (weak signal level).
17) Repeat steps 2 – 13.

### Calibration examples

**Calibration Test A-1 - RF signal level measurement example –** RF signals for each test were measured using the spectrum analyzer channel power measurement to measure the total power contained in a 30 kHz bandwidth. The spectrum analyzer plots in Figure 10 and Figure 11 show the analyzer power calculation as displayed on the screen.

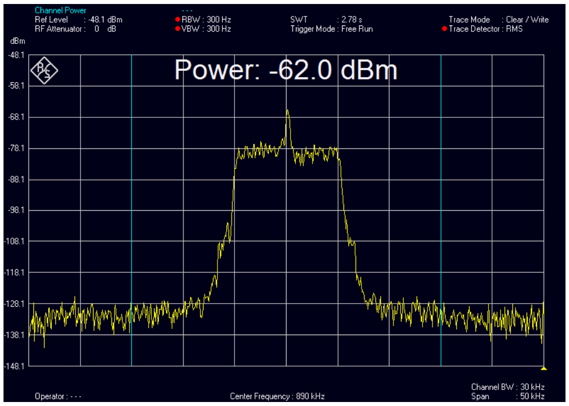



Figure 10. All-digital signal 30 kHz channel power

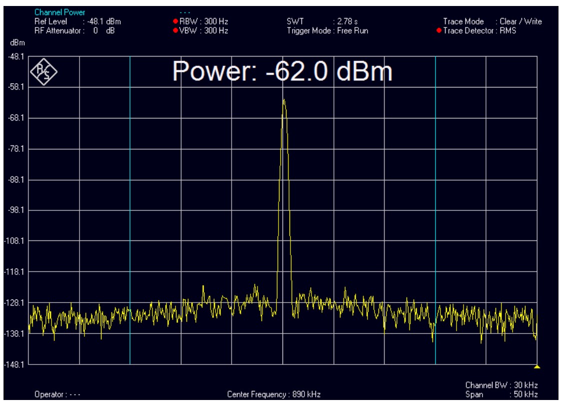



Figure 11. Unmodulated analog signal 30 kHz channel power

**Calibration Test A-2 - RF spectral occupancy** – the spectrum plots in Figure 12 through Figure 14 show the RF spectral occupancy for analog pulsed USASI modulation (Figure 12) and all-digital AM modulation (Figure 13 and Figure 14).

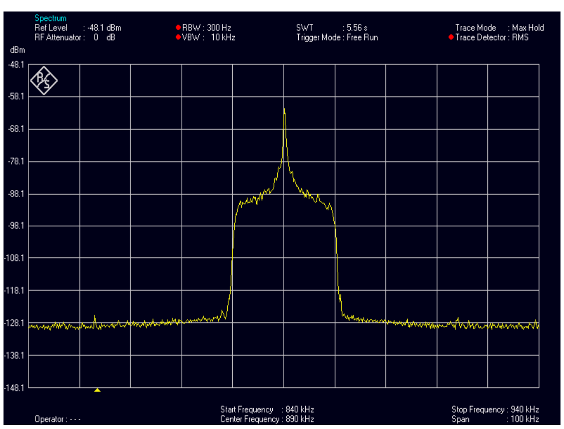


Figure 12. RF spectral occupancy with analog pulsed USASI modulation

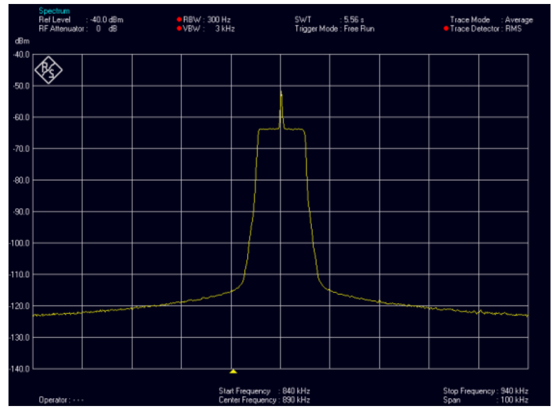


Figure 13. RF spectral occupancy with all-digital AM modulation

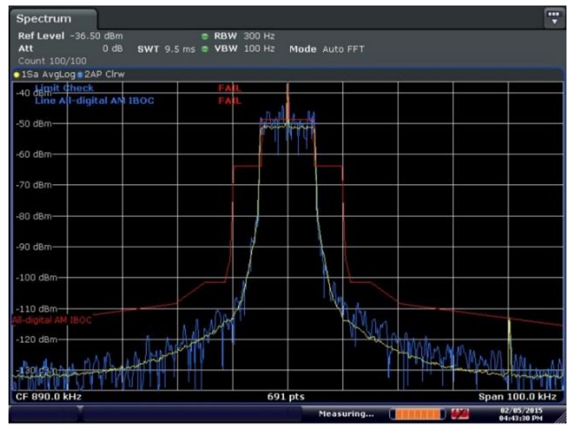



Figure 14. RF spectral occupancy with all-digital AM modulation showing extended sideband noise floor

**Phase-offset signal examples, tests 1-4** – 0° phase locked carriers were set using the procedure described in Appendix 1. An oscilloscope was used to set and verify that the two carriers were frequency and phase locked to each other.

The Lissajous pattern was used to set the carriers as close as possible to 0° phase difference. This XY mode plot in Figure 15 shows the signal from exciter #1 on the X axis and the signal from exciter #2 on the Y axis.

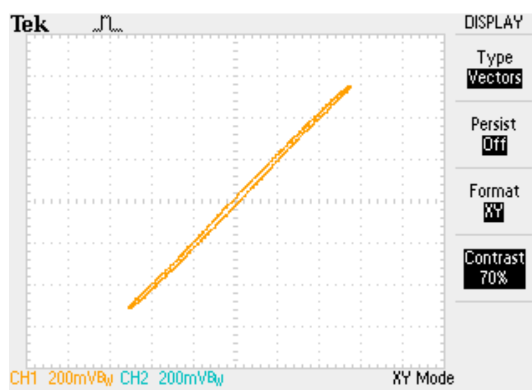



Figure 15. Lissajous pattern corresponding to 0° phase locked carriers

When the signals are in phase there will be a single 45° line (X = Y). Figure 16 is the standard amplitude vs. time plot which also demonstrates the signals exactly overlay each other.

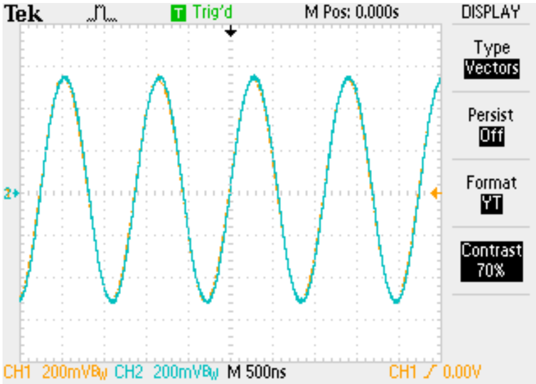



Figure 16. Amplitude vs. time plot showing 0° phase lock

**Phase-offset signal examples, tests 5-8** – 90° phase locked carriers were set using the standard oscilloscope display. The phase is adjusted so that the peak of one wave occurs at the zero crossing of the other signal. The plot is shown in Figure 17 with the arrows added to show where the peak and zero crossing match. The Lissajous pattern for a 90° phase offset is a perfect circle which is difficult to precisely determine. This method was found to be more accurate for the 90° phase offset measurements.

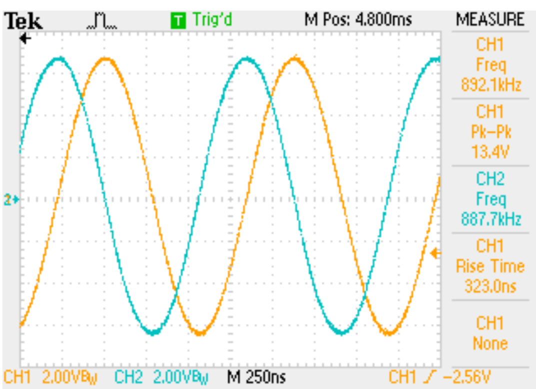



Figure 17. Amplitude vs. time plot showing 90° phase lock

Test procedures followed for these laboratory tests are detailed in Appendix 1. Phase 1 tests were performed in a sterile, noise-free environment.

**Phase-offset signal examples, tests 9-12** – like the 0° offset, the 180° phase was set using a Lissajous pattern. For two signals 180° out of phase, X = -Y or a -45° line on the XY mode plot. Again, the plot on the right is the typical amplitude vs. time plot which also demonstrates the signals are as close as practical to 180° out of phase.

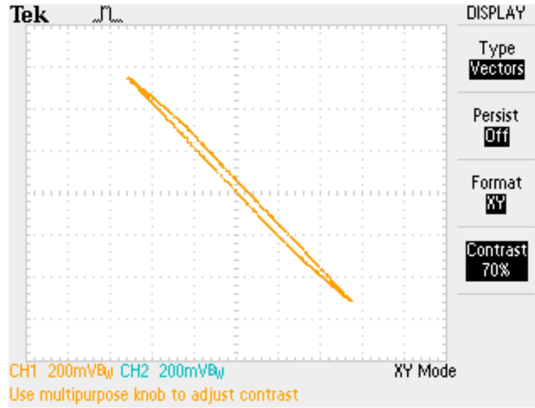



Figure 18. Lissajous pattern corresponding to 180° phase locked carriers

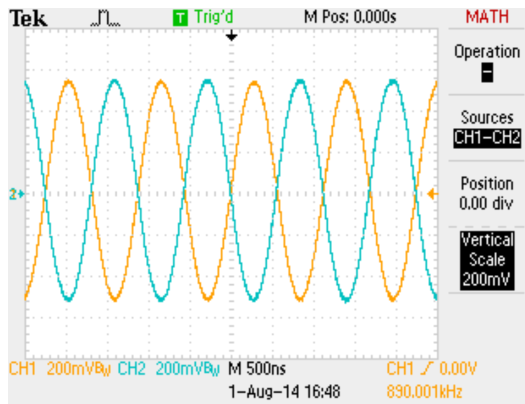



Figure 19. Amplitude vs. time plot showing 180° phase lock

**Frequency-offset signal examples** – a diode detector circuit was used to precisely determine the frequency difference in two carriers. The plot below shows the sine wave output of the diode detector as shown on the oscilloscope. The cursor function of the oscilloscope was used to show 1 Hz frequency when measured between the peaks of the waveform (red arrows). For the actual tests, the output of the diode detector was connected directly to the unbalanced input of the Audio Precision. The Audio Precision was then used to precisely set the frequency of the undesired exciter to 1 Hz, 2 Hz, and 5 Hz above or below the desired carrier as needed. The value of the exciter DAC was modified to set the frequency and verify that the frequency of the undesired signal was above or below the desired signal.

## Test results

Detailed SNR results (for analog desired signals) and threshold of audio interference results (for digital desired signals), from the tests listed in Table 4 and Table 5, are provided in Appendix 2. Additionally, results from tests 13, 14, 13-2 and 14-2 are graphed and included below as Figure 21 through Figure 26:

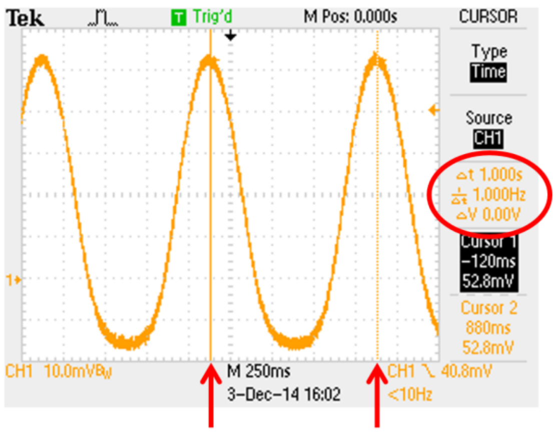



Figure 20. Oscilloscope plot showing setting of 1 Hz frequency offset

**Figure 21** – shown in this graph are audio SNR results for receiver #2 for both Phase 1 (no RF noise, desired signal level of -62 dBm) and Phase 2 (with added RF noise, desired signal level of -64 dBm), and for both analog and all-digital undesired signals. A number of interesting observations about these lab test results may be made from this graph:

- Data points corresponding to high values of D/U (up to 70 dB) represent performance with little or essentially no co-channel interference. Consequently, it is clear from this graph that for this receiver, for Phase 1 the audio SNR asymptotically approaches about 72 dB and for Phase 2 about 34 dB. Note further, for each Phase, the convergence of the all-digital and analog AM interference cases at higher and higher D/Us to the same asymptotic audio SNR, as expected (since it is the RF noise level, not co-channel interference type, dominating performance at these operating points);
- On the other end, at low values of D/U, clearly co-channel interference is dominating the audio SNR behavior (as opposed to added RF noise which dominates for high values of D/U). This can be seen since, for both the analog and all-digital interferer cases, the Phase 1 and Phase 2 test results converge as the D/U values reduce, ultimately becoming the same values for D/U's of 20 through 0 dB (for all-digital interference) and 10 through 0 dB (for analog interference);
- Note that data was obtained at the 26 dB D/U measurement point; this is the point corresponding to the protected contour for co-channel AM stations, that is, at the desired station's protected contour, the maximum D/U ratio for a co-channel interfering station is 26 dB.[5] Strictly speaking, this 26 dB D/U operating point is relevant only at the 0.5 mV/m desired signal level (the defined protected contour), which for the purposes of this laboratory test corresponded approximately to the -76 dBm operating point (discussed above under "Establishing RF signal levels for testing");
- Referring to the Phase 1 curves, this data shows that for receiver #2, for the "ideal" (no environmental RF noise) case, the all-digital AM signal is a stronger interferer than the analog AM signal (into a desired analog AM signal) by approximately 10-15 dB;
- Referring to the Phase 2 curves, this data shows that for receiver #2, for the "real world" (with added RF noise) case, the simulated environmental RF noise is masking the impact of the co-channel interference (both all-digital and analog) for values of D/U greater than approximately 30 dB. As the D/U is reduced from this value, the different impact of all-digital versus analog AM co-channel interference becomes apparent, as was true in the case with no added RF noise (Phase 1 data);
- Since this graph depicts operation (for Phase 2) at a desired signal level of -64 dBm, the most interesting operating point on the (Phase 2) curves is for a D/U of 38 dB. This corresponds to the interfering signal level that would exist if a 26 dB D/U relationship existed at the 0.5 mV/m protected contour (in this case, corresponding to a desired signal level of -76 dBm). Since -64 dBm is 12 dB higher than -76 dBm, the D/U corresponding to the 26 dB D/U operating point is also 12 dB higher which is 38 dB D/U;
- Comparing the desired analog audio SNR at the 38 dB D/U operating point for the all-digital and analog interference cases, the difference observed here is about 2 dB. A subjective evaluation by the authors (and other expert listeners) of the audio recordings made at this operating point for these two cases reveals that from a listening standpoint, there is essentially no difference in audio quality between the two cases.

**Figure 22** – all of the curves in this Figure represent Phase 2 data for receiver #2:

- There are three sets of curves, corresponding to the three tested desired RF signal levels of -76 dBm (approximating the 0.5 mV/m contour), -64 dBm (2 mV/m contour) and -56 dBm (5 mV/m contour). Note that the -64 dBm set of curves also appears in Figure 21;
- For the -56 dBm set of curves, note that the asymptotic audio SNR for high values of D/U (representing little or essentially no interference) is 45 dB. This is by design, since as previously discussed, for the Phase 2 tests the RF noise level was adjusted so as to establish an audio SNR of 45 dB at the approximate 5 mV/m contour;
- Data taken for the other two desired RF *signal* levels was collected using the same RF *noise* level established for the -56 dBm signal level (*i.e.*, only the desired signal level is changed between cases, not the RF noise level). Consequently, note that the *difference* between the asymptotic audio SNR for the other two cases is approximately the same as the difference between the

[5] See FCC rules, 47CFR§73.182.

desired RF signal levels: ~ 35 dB (audio SNR difference of 10 dB for RF signal level difference of 8 dB) and ~ 20 dB (audio SNR difference of 25 dB for RF signal level difference of 20 dB). In each of these other two cases, the measured asymptotic audio SNR is actually greater than the change in RF signal level, presumably attributable to nonlinearities in some part of the test system, and likely in the receiver itself since as will be seen in the remaining figures, these audio SNR differences for the other four receivers (shown in Figure 23 through Figure 26) map quite closely to the actual changes in RF signal level;

- As discussed for Figure 21, the operating points of greatest interest are those corresponding to the 26 dB D/U at the 0.5 mV/m contour. Mapping this operating point to the three desired RF signal levels tested, these operating points are 26 dB D/U for -76 dBm, 38 dB D/U for -64 dBm, and 46 dB D/U for -56 dBm. Referring to Figure 22, at each of these points it is observed that the audio SNR for the all-digital and analog AM interference cases differ by approximately 2 dB, which is a negligible amount from a listener standpoint.

**Figure 23 - Figure 26** – these graphs are similar to the one just discussed for Figure 22, for receivers #1, #3, #4, and #5, respectively. Note that for receivers #3, #4, and #5, data was only collected up to the point where the audio SNR for the all-digital and analog AM interference cases had converged (hence no data points shown for the 60 and 70 dB D/U operating points).

## Analysis

Extensive testing (described above) was conducted on a variety of consumer receivers to quantify the impact of co-channel interference that might be expected with both analog and all-digital signals operating on the same frequency. In order to have a baseline for comparison, identical tests of both analog and digital interferers were performed. Once the impact of analog interference was known, the potential impact of all-digital interference can be compared.

**Co-channel analog AM desired tests (Phase 1)** – because of the predominance of analog modulation on the AM broadcast band, a great deal of attention was paid to the potential of all-digital interference to analog signals. Through experimentation, it was found that this interference could be minimized by phase-locking (*i.e.*, no frequency offset, either exactly in-phase or exactly out-of-phase) the desired and undesired carrier frequencies to one another. Under these conditions, test results indicate that all-digital interference typically degrades analog signal-to-noise ratios approximately 10.5 dB more than an equal amount of analog interference (with no added RF noise present).[6]

If all AM broadcasters were to perfectly synchronize their analog and digital transmitter carriers,[7] varying delays in signal propagation among multiple transmitter sites would result in differing phase relationships as perceived by far-field receiver antennas. Thus, realizing the ideal phase relationships described above can only be assured in a lab environment.

Tests revealed much greater signal-to-noise degradation when analog and all-digital carriers were phase-locked at ninety-degrees. With this carrier relationship, analog signal-to-noise is worsened by approximately 23 dB in the presence of an all-digital signal (again, with no added RF noise present).[8]

Tests with desired and undesired carrier frequencies separated by 1, 2, and 5 Hz from one another reveal all-digital signal-to-noise ratio degradation of approximately 14.5 dB. This stands to reason because these offset carrier frequencies will rotate from being in-phase, through ninety-degrees, to an out of phase condition at a 1 Hz, 2 Hz, and 5 Hz rate. Thus, the measured signal-to-noise figure tends to average the best and worst case signal-to-noise conditions discussed above.

It should be noted that these Phase 1 laboratory results, obtained with no added RF noise, are useful for characterizing the ideal performance of the system (as well as the laboratory test setup) but are not reflective of interference performance in the real world where there is substantial RF noise in the AM band (the situation modeled in Phase 2).

**Co-channel all-digital AM desired tests (Phase 1)** – as expected, all-digital signals are very robust in the presence of analog interferers. With desired and undesired carriers locked or within 1 Hz of one another,[9] the undesired analog signal amplitude can be as great as 6 dB less than the desired all-digital signal before any degradation is detected in the (digital) audio signal. This is a 20 dB or more improvement over the current 26 dB D/U interference standards for analog AM.

Undesired analog signals that are further off-frequency (*e.g.*, 2 and 5 Hz) were found to have a greater impact on the all-digital signal. Tests 19, 23, 31, and 35 show significant increases in interference potential from co-channel analog interferers, with the worst case being ~14 dB D/U. These test results suggest that all-digital stations would benefit from a one hertz carrier frequency tolerance standard.

As was shown for the analog AM desired signal, the all-digital AM signal has a greater interference potential to other all-digital AM signals than does an analog AM interferer. The range of D/U ratios at which the first effects of all-digital interference were detected is between 13 and 16 dB D/U with an average of 13.5 dB D/U. Because this is a much lower threshold of interference than the analog-to-analog D/U of 26 dB, the results suggest that if all AM stations were digital, co-channel interference would be less, thus potentially increasing groundwave coverage for a given power level and carrier frequency.

[6] See Tests 1, 2, 9, &10.
[7] Using GPS or some other means.
[8] See Tests 5 & 6.
[9] See Tests 3, 7, 11, 15, & 27.

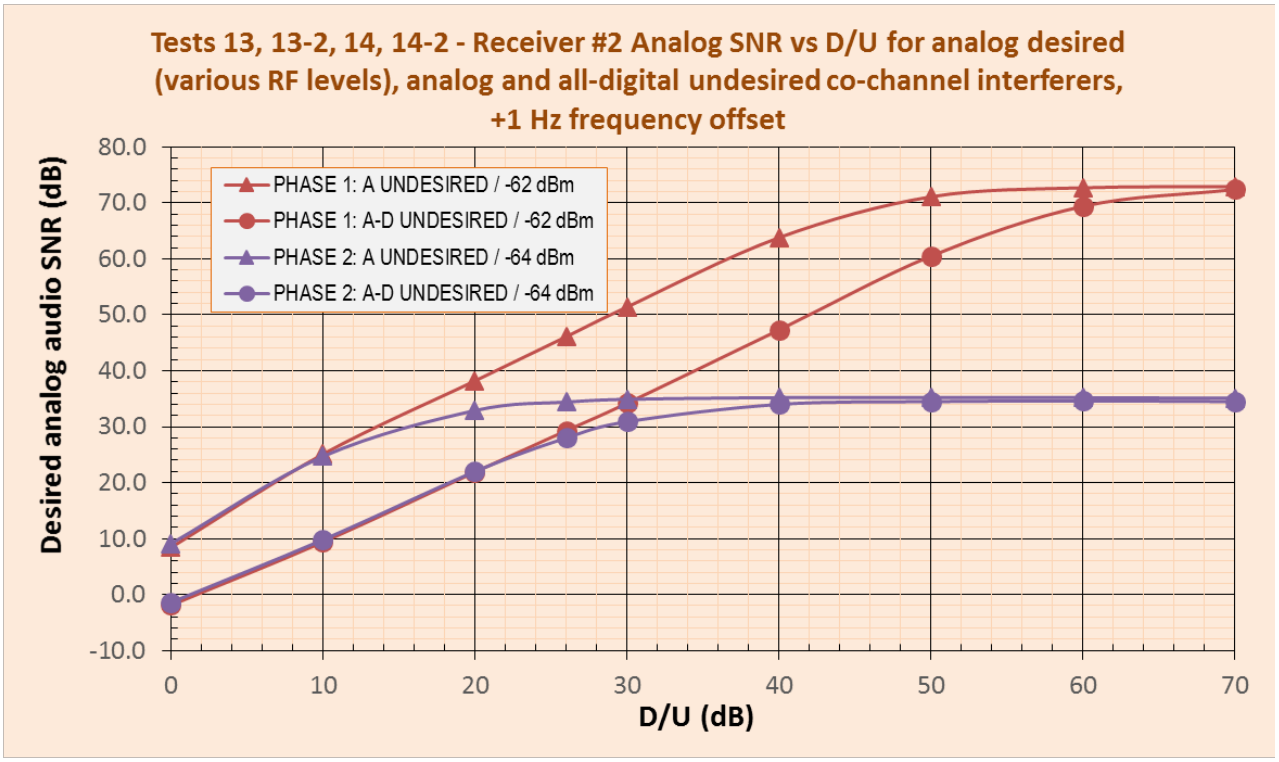



Figure 21. Comparison of SNR performance for receiver #2 without (Phase 1) and with (Phase 2) simulated environmental RF noise

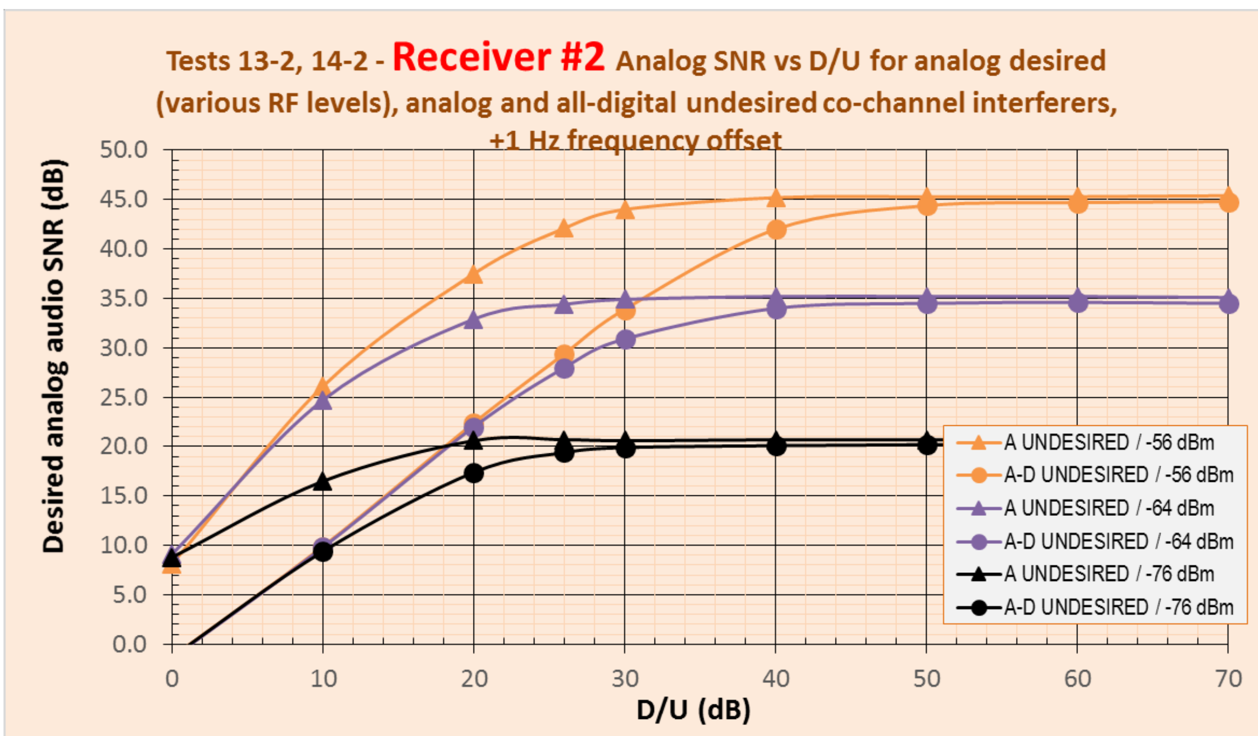



Figure 22. Phase 2 test results for receiver #2

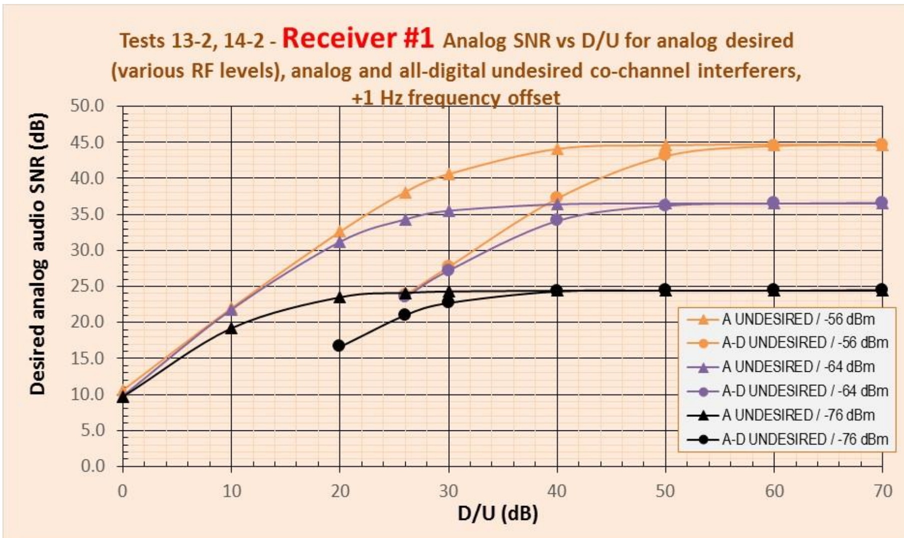



Figure 23. Phase 2 test results for receiver #1

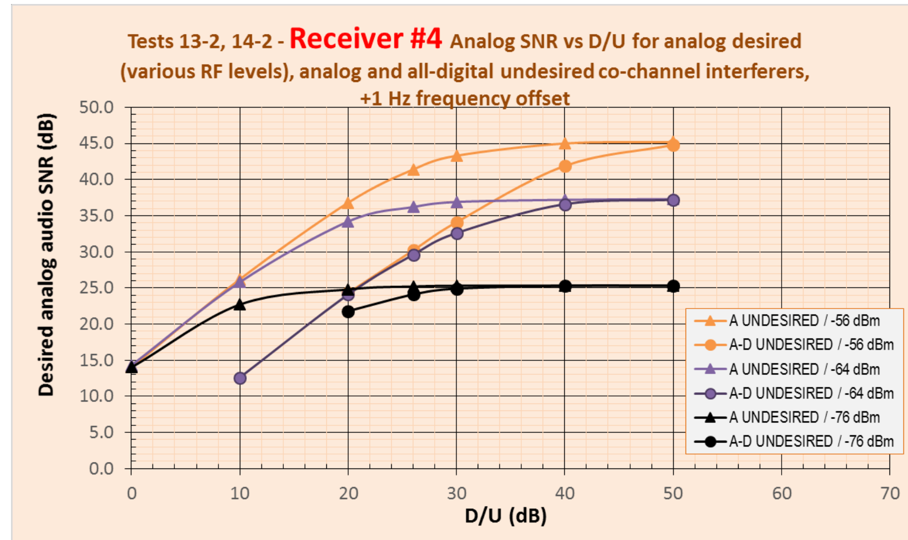



Figure 25. Phase 2 test results for receiver #4

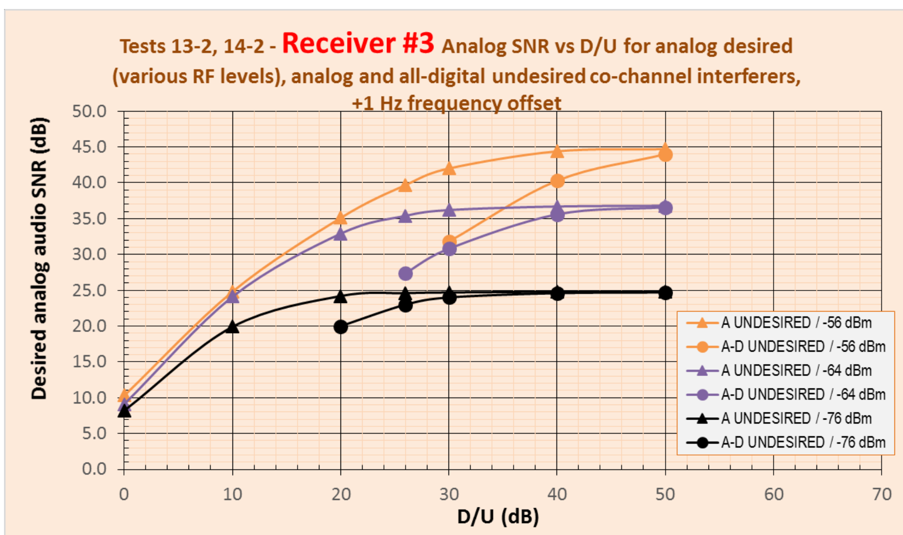



Figure 24. Phase 2 test results for receiver #3

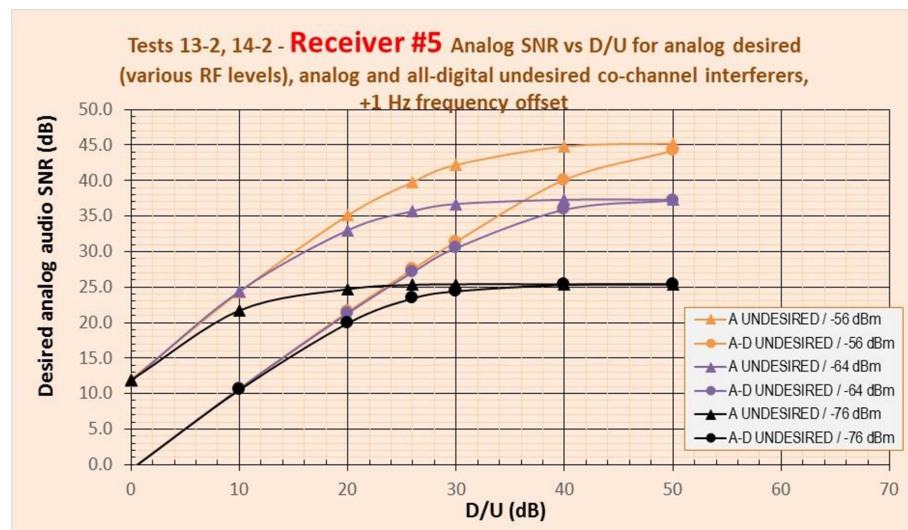



Figure 26. Phase 2 test results for receiver #5

PREVIOUS VIEW

**Co-channel analog AM desired tests with AWGN (Phase 2)** – as discussed previously, the -76 dBm desired RF signal level was selected to approximate a field strength of 0.5 mV/m. The FCC's allocations process protects most AM stations from objectionable interference at that groundwave signal level. Consequently, and as noted above, the points of interest in the data are 26 dB D/U for -76 dBm (representing operation at the protected contour), 38 dB D/U for -64 dBm and 46 dB D/U for -56 dBm (well within the protected contour).

Focusing on the values corresponding to the protected contour, as shown in the tables of Appendix 2 (specifically, the tables for tests 13-2 and 14-2), results for the -76 dBm signal level indicate relatively small differences in desired audio SNR whether the interfering signal was analog or all-digital, especially when compared with the corresponding values obtained from the Phase 1 portion of the test. Expert analysis of audio recordings by the authors and others confirmed that co-channel noise (whether analog or all-digital in nature) was almost completely masked by the added AWGN at these protected contour operating points (*i.e.*, 26 dB D/U for -76 dBm, 38 dB D/U for -64 dBm, and 46 dB D/U for -56 dBm). As the desired signal strength increases (representing movement towards the desired signal), this situation only improves. As the desired signal strength decreases (representing movement away from the desired signal), this represents the region where the desired signal is no longer protected from co-channel interference, outside of the station's protected contour.

**Receiver performance** – during the co-channel analog desired testing it was observed that in certain cases, digital receivers could detect the presence of a digital undesired signal at relatively large D/U ratios. In some receivers, perfectly receivable analog reception would be muted even when the digital signal level was extraordinarily weak. This caused a loss in analog coverage at signal levels well below the 26 dB D/U level of analog-into-analog interference.

For example, using receivers #2 and #3 at +1 Hz and -1 Hz frequency offset, the digital undesired signal would mute the analog desired signal when the digital undesired signal was 40 dB below the analog. The analog signal would remain muted or the digital signal would be recovered for the remainder of the test. For the same receivers (#2 and #3), this phenomenon occurred at 50 dB below the analog during the zero degree phase locked test (Test #2). For receivers #1 and #4, this occurred with the digital signal at 20 dB below the analog, higher than the currently defined 26 dB D/U of analog interference.

It was also noted that this "capture effect" exhibited some hysteresis behavior in some receivers. In some cases, the capture effect did not release the muted (desired) analog audio until the (undesired) digital signal was reduced to well below the level at which it was initially captured. In other words, a receiver that captured the digital signal at 20 dB D/U (desired is 20 dB below the analog) continued to mute the analog audio until the digital signal was reduced to 40 or 50 dB D/U. This symptom was most pronounced when the signals were phase locked. Thoroughly testing this hysteresis behavior was outside the scope of these tests but apparently this behavior is receiver-specific.

**Receiver muting in analog mode** – two receivers used in this testing allowed for the ability to select a digital audio mode. Mode choices for receiver #2 were "HD enabled" or "HD disabled." This worked as expected, with the "HD disabled" mode only permitting analog signals to be received. Results for both modes are shown in Appendix 2. With receiver #4, the receiver mode choices consisted of "Digital," "Analog," and "Auto." Tests were done in "Digital" or "Analog" mode as indicated in Appendix 2. It was discovered that when in "Analog" mode, the receiver would sometimes detect digital co-channel signals and mute the analog audio, resulting in "interference" to an analog signal which would have otherwise been listenable.

## Audio recordings

In addition to the interference measurements described above, audio recordings were made for demonstration purposes and for possible use in future subjective evaluation. A range of audio formats were selected to represent the types of programming typically found on AM radio stations. All content used was from the uncompressed WAV file recordings or the original CD saved in WAV format. The following audio files were selected for use as typical AM radio content:

- Male spoken voice (FCC license renewal statement)
- Female spoken voice (a PSA on fall foliage in New England)
- Country Music – "*Don't It Make My Brown Eyes Blue*" by Crystal Gayle
- Pop Music – "*Tuesday Afternoon*" by Moody Blues

For the analog desired tests, each selection was recorded with each of the other three audio tracks. To accomplish this, audio editing software was used to compile 30 seconds clips of the 4 audio selections summed into mono track and repeated three times for the "desired" audio track. The 30-second clips of the undesired audio were then added to the right channel such that each desired selection was paired with the remaining three audio recordings.

There are 12 total clips since the same track is not used as both a desired and an undesired source at the same time. The resulting content of the six-minute audio source file is shown in Table 6.

The Audio Precision test set automation capability was used to play both desired (left channel) and undesired Audio (right channel) as shown in Figure 27. The audio patch bay was then used to patch each channel into the proper audio processor as detailed below. In addition, the automation capabilities of the Audio Precision were used to record the resulting analog audio output from each receiver into individual uncompressed WAV files for each D/U level.

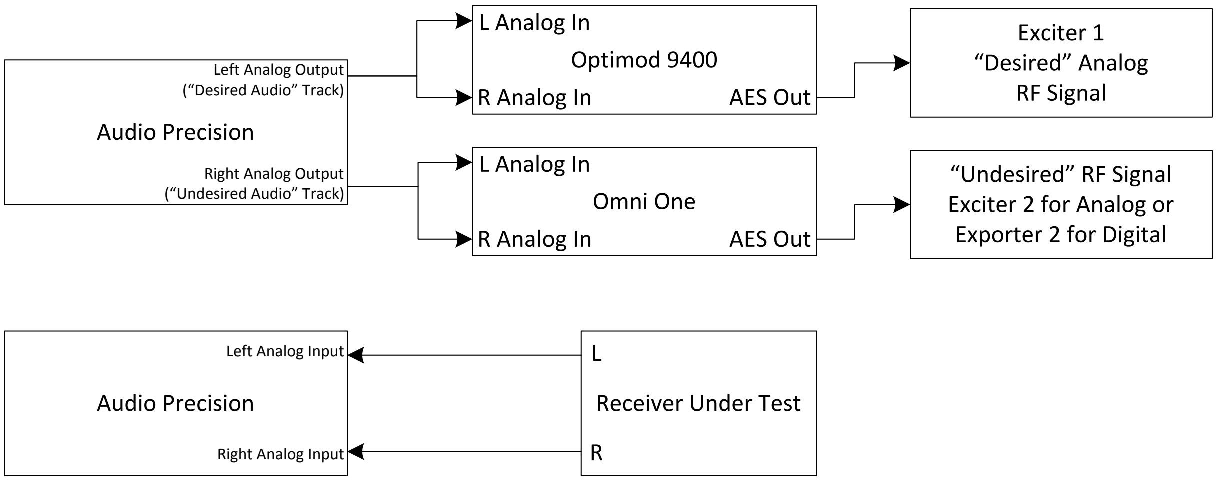



Figure 27. Block diagram illustrating the use of the Audio Precision test set to simultaneously generate both the desired (left channel) and undesired (right channel) audio signals

For the tests using a digital undesired signal, the program content does not affect the modulated signal, therefore a 500 Hz tone modulated the undesired digital signal. The + 1, +2, and +5 Hz frequency offset tests were recorded with both analog and digital interferers (Tests 13, 14, 17, 18, 21, and 22.) The -1 Hz offset test was also run for analog undesired (Test 25). For Digital undesired tests, Receiver #2 and #4 were recorded in both modes of operation.

Table 6. Organization of audio tracks for six-minute audio source files

| Time (m:ss) | Left (desired) | Right (undesired) |
|---|---|---|
| 0:00 | Male voice | Female voice |
| 0:30 | Female voice | Brown Eyes |
| 1:00 | Brown Eyes | Tuesday Afternoon |
| 1:30 | Tuesday Afternoon | Male voice |
| 2:00 | Male voice | Brown Eyes |
| 2:30 | Female voice | Tuesday Afternoon |
| 3:00 | Brown Eyes | Male voice |
| 3:30 | Tuesday Afternoon | Female voice |
| 4:00 | Male voice | Tuesday Afternoon |
| 4:30 | Female voice | Male voice |
| 5:00 | Brown Eyes | Female voice |
| 5:30 | Tuesday Afternoon | Brown Eyes |

These recordings were generated separately from the signal-to-noise tests because of the difference in test setup and automation. The resulting tests generated 267 audio files which can be used for comparison of various D/U levels and various receiver operations in the presence of analog and digital interferers. To avoid confusion the audio recordings were kept in separate directories by test number and receiver number/mode. The tables of recordings filenames, dates, and file sizes are included in Appendix 3.

## Summary and future activities

With the all-digital AM field and laboratory test projects, NAB Labs has significantly expanded the knowledge and understanding of the HD Radio all-digital AM system. Field test results have characterized the coverage performance for a variety of station types using readily-available consumer radio receivers. Lab test results have provided information on the co-channel interference behavior of the all-digital AM signal into both analog and all-digital desired signals. And, a significant number of audio recordings under a variety of co-channel interference scenarios have been captured for future reference.

As mentioned in the field test paper [1], a possible future all-digital AM-related testing and study activity pertains to RF mask compliance. As briefly mentioned in [1], the observed level of compliance with the MA3 RF mask specified in NRSC-5 at the field test stations varied. This mask was specified by iBiquity prior to the widespread development and deployment of AM HD Radio transmission equipment and is likely to be re-evaluated to take into account operational information and an assessment of the realizable performance of AM facilities.

## Acknowledgments

The project manager for the work described in this paper was Mr. Layer. Messrs. Rhodes and Ryson were the principal investigators and were responsible for construction of the NAB Labs radio test bed. Other significant contributors to this work include Mr. Lynn Claudy, Sr. VP Technology, NAB, Mr. Milford K. Smith, VP Radio Engineering, Greater Media, and Mr. Russ Mundschenk, Senior Field Test and Implementation Manager, DTS, Inc. (formerly iBiquity Digital Corporation). The authors also gratefully

acknowledge the support of Mr. Sam Matheny, NAB EVP and CTO.

## References

[1] *NAB Labs All-digital AM Test Project,* 2015 NAB Broadcast Engineering Conference Proceedings, April 2015, pp. 19-44

[2] *AM IBOC DAB Laboratory and Field Testing: Third Report to the National Radio Systems Committee*, iBiquity Digital Corporation, January 4, 2002

[3] *Evaluation of the iBiquity Digital Corporation IBOC System - Part 2- AM IBOC*, National Radio Systems Committee, April 6, 2002

# Facility Upgrades For Full-Time All-Digital HD AM Broadcasting: A Case Study

**David Kolesar**
**Hubbard Radio**
**Washington, DC**
dkolesar@wtop.com

**Mike Raide**
**Xperi Corporation**
**Columbia, MD**
Mike.Raide@xperi.com

**Abstract -** *WWFD (820 kHz, Frederick MD), owned by Hubbard Radio, has engaged in a cooperative effort with Xperi Corporation to become the first AM broadcast station to transmit using the HD Radio all-digital MA3 mode full-time. The MA3 waveform provides multiple advantages over the "hybrid" MA1 waveform currently in use for HD Radio AM broadcasting, relating to spectral utilization and robustness. In order to broadcast the MA3 waveform, WWFD evaluated its phasor and antenna termination units (ATUs), as well as its transmitters. Modifications to these were performed in coordination with the appropriate experts – Kintronic Labs along with Cavell, Mertz and Associates for the antenna system, and Broadcast Electronics, Nautel, and GatesAir for the transmitters. There was a regulatory aspect to this project as well, as MA3 is not currently an authorized mode of operation for AM broadcasters in the United States. With guidance from Cavell Mertz and Associates, an experimental authorization to operate WWFD under this mode was submitted to the Federal Communications Commission (FCC) and subsequently granted, and WWFD commenced digital operations on July 16, 2018. Results from preliminary drive tests and observations have been encouraging, and have revealed some unforeseen transmitter issues that are being addressed by station engineers and equipment manufacturers.*

## HYBRID VS. ALL-DIGITAL WAVEFORMS

One of the most common complaints about the current (hybrid) system of HD Radio AM broadcasting (also known as MA1, see Figure 1) is its spectral utilization; that is, it requires +/- 15 kHz of radio frequency (RF) bandwidth to transmit both an analog and digital signal. The analog signal is usually restricted to 5 kHz audio bandwidth, and the digital carriers often "bleed" into the analog signal in receivers with wide intermediate frequency (IF) bandwidth, causing a distinct hiss in the receiver. Additionally, the digital carriers are 30 dB lower in amplitude than the analog carrier, which limits digital signal robustness and reception range. The MA1 waveform is viewed as a compromise at best, allowing digital reception close to the transmitter while maintaining analog service over the full station coverage area.

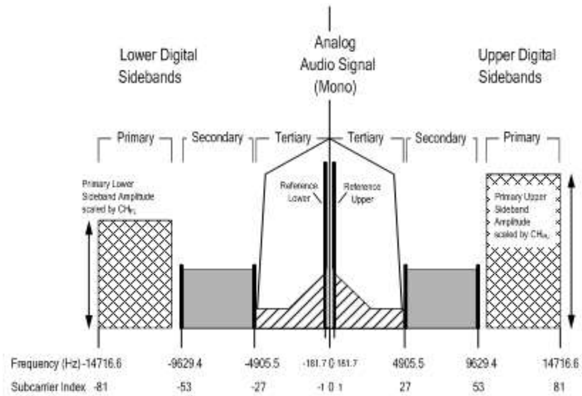



FIGURE 1: THE MA1 (HYBRID) WAVEFORM [1].

WWFD is a music-oriented station, broadcasting an Adult Album Alternative (AAA) format, with an FM translator (W232DG, 94.3 MHz, 160 watts ERP) covering its city of license as well. Since most of WWFD's listeners migrated to the FM translator shortly after it signed on in July 2017, the importance of maintaining analog AM service for WWFD's music format was greatly diminished. As a result, the possibility of turning off the analog carrier and replacing it with the all-digital MA3 mode is an intriguing one. Several benefits of MA3 are observed. Less bandwidth is required, as the digital signal occupies +/- 10 kHz (or +/- 5 kHz in the Core mode), resulting in less adjacent-channel interference than the MA1 waveform. The effective data throughput increases to approximately 40 kbps over the 20 kbps achieved with the MA1 waveform, resulting in higher-fidelity stereo audio, and opens up the possibility of multicasting and data services such as "Artist Experience." Such services, combined with the increased audio fidelity of the MA3 signal, allow AM broadcasters to achieve aural and visual parity (through the display of visual metadata such as album artwork) with other services on a car dashboard, such as FM HD Radio, streaming services (such as Pandora), and SiriusXM satellite radio. Most importantly, the primary digital carriers of the MA3 waveform are only 12 dB down from the pilot carrier (which is the CW on the center channel, see Figure 2), which means that most of the transmitter power is dedicated to the digital carriers (as opposed to MA1), resulting in a significantly more robust digital reception experience than the hybrid mode can provide.

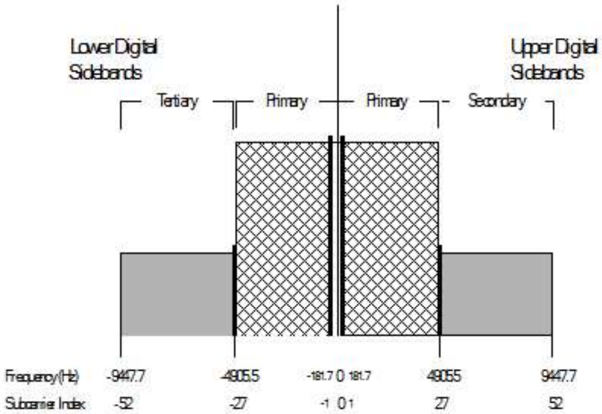



FIGURE 2: THE MA3 (ALL-DIGITAL) WAVEFORM [1].

Given these factors, it became advantageous for WWFD to switch to the MA3 mode, and to use the W232DG translator to promote the higher fidelity and increased reception area of the digital AM signal for listeners with HD Radio receivers who may be driving out of the service area of the FM translator.

## THE ANTENNA SYSTEM

The first task to prepare WWFD for all-digital operation was to examine the antenna system. The station utilizes two series-fed towers 73.5 degrees tall with 26.5 degrees of top-loading, with a tower spacing of 60 degrees (Figure 3). It operates at 4,300 watts non-directional from one tower during the daytime, and utilizes both towers for nighttime operation at 460 watts with a cardioid pattern.

FIGURE 3: THE WWFD TRANSMITTER FACILITY.

Tom King from Kintronic Labs in Bluff City, TN evaluated the day and night performance of the antenna, and found it inadequate for all-digital transmission (WWFD was previously an analog-only station, having never broadcast using the MA1 mode). A "rule of thumb" to evaluate an AM antenna system for digital operation is to ensure that the Standing Wave Ratio (SWR) is 1.4:1 +/- 15 kHz from the center frequency: WWFD's was 1.8:1 at 10 kHz for the day mode, and 2.1:1 at 10 kHz for the night mode.

Subsequently, the entire antenna system had to be documented: the schematic was verified, the components were described and measured, and any unusual physical situations had to be noted (isocouplers, abandoned transmission lines on the towers, etc.). Since the antenna array was in substantial adjustment, self and mutual impedances of each tower were measured with an impedance bridge. Kintronic Labs created a model of the antenna system using this data, which allowed them to redesign the phasor and ATU networks for both optimal phase shifts for maximum bandwidth and the minimum of new components to be purchased.

FIGURE 4: REMOTE PICKUP UNIT (RPU) TRANSMISSION LINE BONDED TO TOWER FEED, SUBTRACTING 10 OHMS OF CAPACITIVE REACTANCE AND ADDING 2 OHMS OF RESISTANCE TO THE TOWER.

A number of issues complicated the effort to achieve enough bandwidth for all-digital transmission. The towers are less than 90 degrees in physical height, so the tuning units necessarily are restricted in bandwidth. The presence of a station on 930 kHz less than a mile away, and another station being diplexed on WWFD's towers at 1670 kHz mean that filter and detuning networks are present: over time these networks had become somewhat detuned as the environment around the transmission site has urbanized. A studio-to-transmitter link (STL) dish to a sister FM station (WTLP) was added to Tower 1, with the accompanying isocoupler affecting the tuning and bandwidth of the system. An abandoned Remote Pickup Unit (RPU) antenna and line on Tower 1 was present. It was discovered that when the RPU isocoupler inside the ATU building was removed (perhaps 30 years ago), the transmission line from the tower had not been bonded to the AM feed line, creating an additional capacitance across the base insulator of the tower (see Figure 4). Inside the phasor, long runs of tubing existed in the original 1961 Gates cabinet: this cabinet was originally designed for 1370 kHz daytime operation only, and subsequent modifications included day/night relays and a frequency change to 820 kHz (along with a tower re-orientation, lengthening, and top-loading) in 1987. All of these modifications needed to be re-examined, and adjustments made in order to make the antenna system resemble what Kintronic Labs had modeled, so that the suggested tuning changes would work as intended.

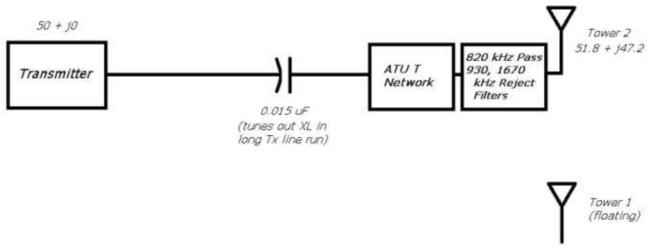



FIGURE 5: WWFD DAYTIME ANTENNA SYSTEM (BLOCK DIAGRAM).

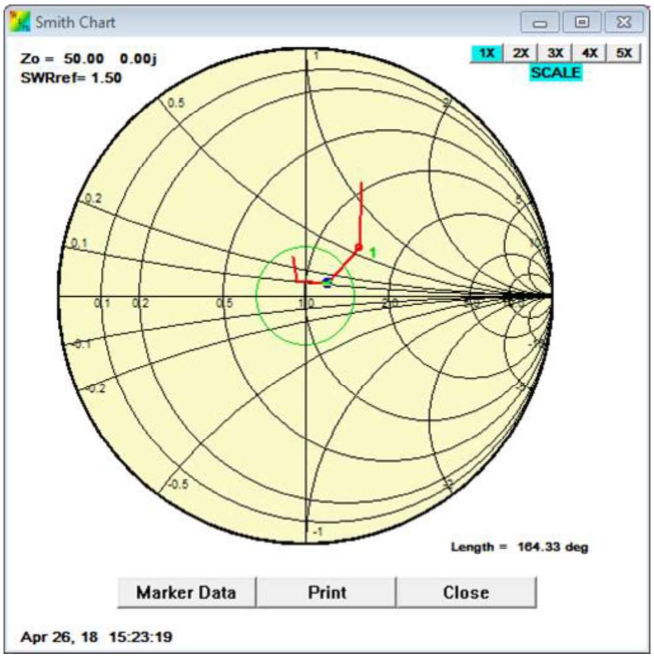
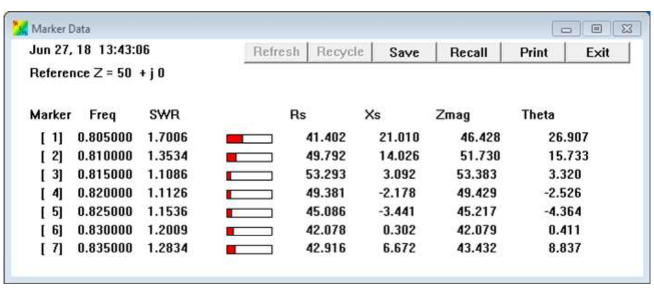



FIGURE 6: WWFD RETUNED DAYTIME ANTENNA SMITH CHART.



Marker Data

Jun 27, 18 13:43:06 Refresh Recycle Save Recall Print Exit

Reference Z = 50 + j 0

| Marker | Freq | SWR | Rs | Xs | Zmag | Theta |
|---|---|---|---|---|---|---|
| [ 1] | 0.805000 | 1.7006 | 41.402 | 21.010 | 46.428 | 26.907 |
| [ 2] | 0.810000 | 1.3534 | 49.792 | 14.026 | 51.730 | 15.733 |
| [ 3] | 0.815000 | 1.1086 | 53.293 | 3.092 | 53.383 | 3.320 |
| [ 4] | 0.820000 | 1.1126 | 49.381 | -2.178 | 49.429 | -2.526 |
| [ 5] | 0.825000 | 1.1536 | 45.086 | -3.441 | 45.217 | -4.364 |
| [ 6] | 0.830000 | 1.2009 | 42.078 | 0.302 | 42.079 | 0.411 |
| [ 7] | 0.835000 | 1.2834 | 42.916 | 6.672 | 43.432 | 8.837 |

FIGURE 7: WWFD RETUNED DAYTIME ANTENNA SMITH CHART MARKER DATA.

The suggested circuit changes were implemented. At the ATUs, the L networks were converted into T networks, allowing the phase shifts to be adjusted for bandwidth optimization. Inside the phasor, the T networks to adjust each tower's phase shift were converted to series LC networks, providing merely "fine-tuning" controls [2] for the larger shifts at the ATUs. Issues that appeared during the documentation phase had to be corrected. The antenna system, having been modified as prescribed, was adjusted in sections starting from the tower and working backwards towards the transmitter. The pass/reject filters at the ATUs were retuned using a Power AIM 120 from Array Solutions; corrections were verified with an impedance bridge under power. The abandoned RPU line, having been bonded to the tower feedpoint on the ATU side of the base insulator, subtracted 10 ohms of capacitive reactance and added two ohms of resistance to Tower 1. This change, more than any other, brought Tower 1's self-impedance much closer to what was modeled: it is believed that when the RPU isocoupler was removed, an operator had simply cranked on the phasor controls until the directional parameters were back in line, without regard to impedance or bandwidth. Inside the phasor, pieces of long tubing were replaced with 7/8" shielded transmission line to prevent interactions between day and night networks. A capacitor was added to counteract a long coaxial cable run to the transmitters (see Figure 5), which were moved almost 20 years ago to a different room, whereas their original location put them adjacent to the phasor cabinet. Many of the above modifications resembled site rehabilitation, counteracting decades of site neglect and poor practices that are likely all too common across the industry.

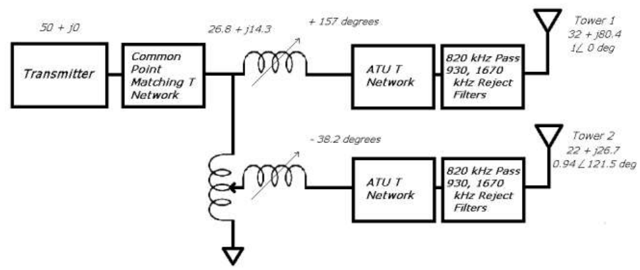



FIGURE 8: WWFD NIGHTIME ANTENNA SYSTEM (BLOCK DIAGRAM)

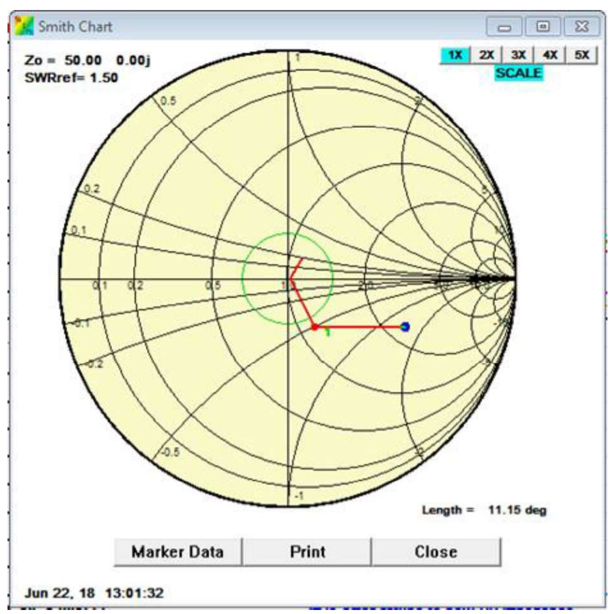



FIGURE 9: WWFD RETUNED NIGHTTIME ANTENNA SMITH CHART.

Marker Data

Jun 27, 18 12:12:30

Refresh | Recycle | Save | Recall | Print | Exit

Reference Z = 50 + j 0

| Marker | Freq | SWR | Rs | Xs | Zmag | Theta |
|---|---|---|---|---|---|---|
| [ 1] | 0.805000 | 1.8532 | 73.216 | 14.718 | 74.681 | 11.366 |
| [ 2] | 0.810000 | 1.3666 | 66.394 | -5.896 | 66.656 | -5.074 |
| [ 3] | 0.815000 | 1.1108 | 51.875 | -4.055 | 52.033 | -4.470 |
| [ 4] | 0.820000 | 1.0949 | 51.867 | 0.636 | 51.871 | 0.702 |
| [ 5] | 0.825000 | 1.1357 | 54.742 | 4.238 | 54.905 | 4.427 |
| [ 6] | 0.830000 | 1.2273 | 60.413 | 3.962 | 60.543 | 3.752 |
| [ 7] | 0.835000 | 1.3065 | 64.992 | 1.363 | 65.006 | 1.201 |

FIGURE 10: WWFD RETUNED NIGHTTIME ANTENNA SMITH CHART MARKER DATA.

Tuning the daytime network, which consists solely of the T network at Tower 2, was fairly simple: the components were adjusted for an impedance of 50 + j0 at the transmitter. Given the modifications and repairs, the bandwidth proved more than adequate, with a measured SWR of less than 1.35:1 at +/- 10 kHz (see Figures 6 & 7). Note that the aforementioned "rule of thumb" would apply to +/- 10 kHz for MA3 operation, and +/- 15 kHz for MA1. (Another benefit of MA3 operation is that antenna systems unable to pass digital carriers in the MA1 mode may be capable of doing so using MA3.) The nighttime antenna system, being a two-tower directional array (see Figure 8), proved to be more complicated. Dummy loads were placed at the input to each ATU, with the Power AIM 120 looking backwards into each network from the antenna side. The matching networks were then set for the complex conjugate of the drive point impedance measured when the array had been in substantial adjustment. With the networks reconnected, the phasor controls were used to put the array back into substantial adjustment, and with a bridge inserted at the output of each port of the phasor, the transmission lines were matched to 50 + j0 using the "cut and try" method. Finally, the input network to the phasor (i.e., the "common point") was adjusted to provide an impedance of 50 + j0 to the transmitter. These procedures are described in detail in a few references; the one used at WWFD was outlined by Jack Layton [3]. With the night network in tune, it was swept for bandwidth, and found to have an SWR of not more than 1.37:1 at +/- 10 kHz (see Figures 9 & 10). With the entire antenna system properly adjusted and capable of passing the MA3 waveform, attention shifted to the transmitters themselves.

## TRANSMITTER SETUP

WWFD utilized two transmitters for analog operation: a Harris Gates Five as the main, and a Nautel AMPFET Five for auxiliary service. The AMPFET Five could not support digital operation, and so was abandoned. A Broadcast Electronics (BE) AM-6A was acquired and installed as the new main transmitter. A Nautel AM IBOC Exciter and BE ASi-10 were obtained to generate MA3 waveforms, and work commenced to set up both transmitters for digital operation (see Figure 11).

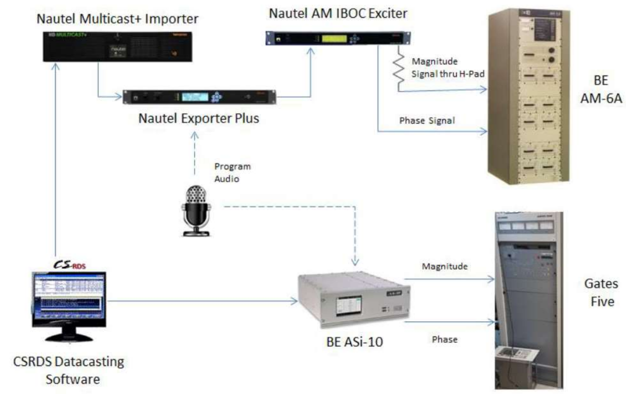



FIGURE 11: WWFD TRANSMITTER CONFIGURATION.

The audio input of each transmitter was connected to the magnitude output of its exciter, and the external oscillator input of each transmitter was connected to the phase output. Testing was first done with the Nautel exciter and AM-6A transmitter, interfacing the balanced magnitude exciter output to the balanced (left) audio input of the transmitter through an H-Pad variable attenuator. The manufacturer's instructions for implementing the hybrid MA1 mode were followed. With the transmitter properly tuned for MA1 operation, the exciter was flipped to MA3 mode. The audio input of the transmitter was then set to not exceed 95 percent negative modulation as indicated on the front panel modulation meter, with the positive peaks far exceeding that – readings above 150 percent modulation are typical. Monitoring the RF output of the transmitter with a spectrum analyzer, the phase delay was adjusted for minimum spectral regrowth. This adjustment is best done with the secondary and tertiary carriers turned off (i.e., in MA3 core mode, with just the primary carriers being transmitted), as some regrowth may be hidden underneath the secondary and tertiary carriers in the full MA3 mode. Having been optimized, the MA3 secondary carriers were turned back on, and the spectral regrowth was rechecked to confirm that at +/-25 kHz from the center of the channel, the regrowth was limited to -65 dBc with reference to the pilot channel, in order to ensure compliance with the NRSC 2 spectral emissions mask.

It was determined that when using the Nautel exciter with the BE AM-6A transmitter, the carrier-to-noise ratio of the secondary and tertiary carriers was insufficient for reliable reception of these carriers. The cause of this phenomenon is currently under investigation, the lines of which include both possible issues in the transmitter itself and further adjustment of exciter parameter settings. In addition to magnitude and phase delay adjustments in the exciter, the other relevant parameter is the I/Q scale factor. The Nautel AM IBOC exciter calls this the Digital Scale Factor, and it appears to be fixed in the exciter's Exgine interface at a value of 6000, optimized for use in Nautel transmitters. This parameter is adjustable in the BE ASi-10 exciter, and testing with this exciter and the AM-6A transmitter is pending.

The Gates Five transmitter was connected to the ASi-10, and adjusted for MA1 and then MA3 transmissions. This setup resulted in lower spectral regrowth when compared to the main transmitter, with improved reception of the secondary and tertiary carriers in tandem with the higher carrier-to-noise ratio. The transmitter proved capable of putting a 3 kW output (as read on the transmitter's power meter) into the station's dummy load. When connected to the antenna system, however, the VSWR protection circuits immediately tripped and reduced the transmitter's output to the night authorization power level. It is believed that the protection circuits are being activated when routed into the relatively imperfect (but still theoretically adequate) antenna system because of the much higher peak-to-average ratio of the MA3 waveform when compared to typical analog modulation. Transmitter power output control circuitry is being examined. The symptoms and possible solutions are under investigation in consultation with the manufacturer. The Gates Five is currently serving as an auxiliary transmitter operating at nighttime power (460 watts).

## Power Measurement

The MA3 mode requires that power be measured differently than a standard analog AM signal [4]. The peak-to-average ratio of the MA3 mode is significantly higher than that of standard amplitude modulation. As a result, the power level meter on the transmitter may not read accurately. Furthermore, if the transmitter is not optimized for the MA3 mode, the peak-to-average ratio may be reduced, leading to a different power level reading than had the transmitter been optimally adjusted. A procedure was devised to confirm that the transmitters are operating in MA3 mode at licensed power. In general, the transmitter is operated in analog mode with an unmodulated carrier, and a channel power measurement is made with a spectrum analyzer on the monitor port. When operating in MA3 mode, the output is adjusted to achieve the same channel power as measured with the unmodulated carrier. This procedure must be done for each licensed power level, as the modulation monitor outputs of most broadcast transmitters are scaled with changing power levels.

The overnight all-digital AM tests conducted by PILOT at WBCN (Charlotte, NC) at the end of 2012 used a power meter with an averaging sensor on the transmitter monitor port [5]. It would be useful to compare the results of this method of power measurement with the spectrum analyzer method outlined above.

## Experimental Authority

Currently, the only legal method of broadcasting using the MA3 mode in the United States is under experimental authority from the FCC. WWFD was granted an Engineering Special Temporary Authority (STA) to operate in this mode for one year, starting July 16th, 2018. Broadcasters have been encouraged by the FCC to experiment with an all-digital service, with appropriate authorization. WWFD's efforts to transmit using the MA3 mode is viewed by the station's engineering staff as a logical continuation of the FCC's AM revitalization efforts, where analog listeners using the station's FM translator are directed back to the HD Radio all-digital AM signal for its larger coverage area, improved sound quality, and metadata experience.

The station's licensed operating parameters do not change under the STA; digital power output will be the same as its licensed analog power, and the directional parameters also remain identical. Operation in the all-digital mode is being supervised both by station and Xperi personnel. Remote control hardware ensures 24/7 monitoring and notification if any station parameters go out of tolerance. No changes to programming have been planned.

## Commission And Drive Tests

Once WWFD was authorized to transmit using the MA3 mode, all-digital broadcasting commenced at noon on July 16th, 2018. Base currents, directional parameters, and monitor points were verified to ensure that the station was operating within licensed parameters. For a qualitative check of field strength, the station's existing field strength meter (in WWFD's case, a Potomac Instruments FIM-21) was checked against a meter specifically designed to handle the MA3 mode (a FIM-4100). The FIM-21 and FIM-41 meters indicate lower field strengths in MA3 than what a FIM-4100 reads, as the latter has passband filters that encompass the entire waveform. As a result, one must compare measurements side-by-side and come up with a multiplication factor for each individual meter (due to variances in the IF filter sections for the FIM-21 and FIM-41 meters, or any superhetrodyne meter) to be used when a qualitative check is desired and a newer meter is unavailable. With parameters verified, drive testing began, which served as a qualitative check on the MA3 implementation at WWFD.

In-vehicle daytime drive-testing, using factory OEM radios, demonstrated that the station's 0.5 mV predicted contour is a good indicator of daytime coverage (see Figures 12 and 13), with reasonable robustness to obstacles that impede analog AM reception: power lines, electrical storms, and passing underneath bridges. Under ideal circumstances, the MA3 primary carriers can be decoded in the daytime down to the 0.1 mV contour: reception reports and drive testing have confirmed coverage at or near Harrisburg, PA, Breezewood, PA, and Cambridge, MD. Critical hours propagation phenomena generally reduce reliable coverage to the 0.5 mV contour. Nighttime reception is generally predicted by the station's Nighttime Interference Free (NIF) contour, noting that wherever an analog carrier to noise Ratio of 20 dB is achieved, the MA3 carrier will generally be received. Early evening reception goes well beyond the NIF; and as co-channel skywave interference increases throughout the evening, coverage retreats to the NIF. In the station's 2.0 mV contour, in-vehicle reception proves to be

solid, without observed dropouts in either the Frederick, MD urban core or underneath bridges.

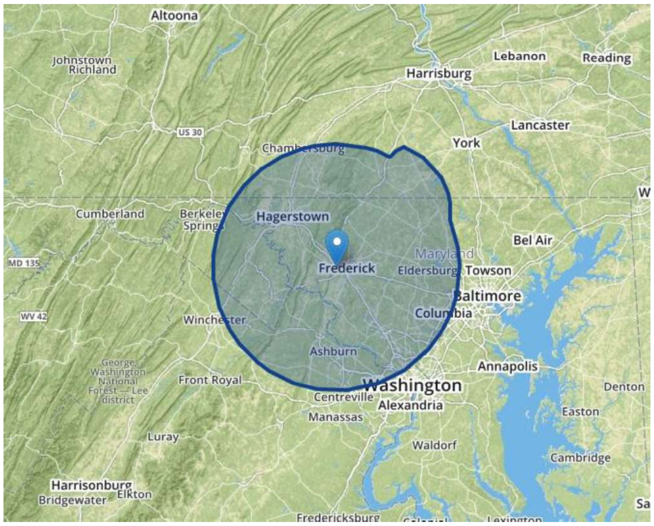



FIGURE 12: PREDICTED 0.5 MV DAYTIME CONTOUR FOR WWFD AS PER THE STATION'S PUBLIC FILE.

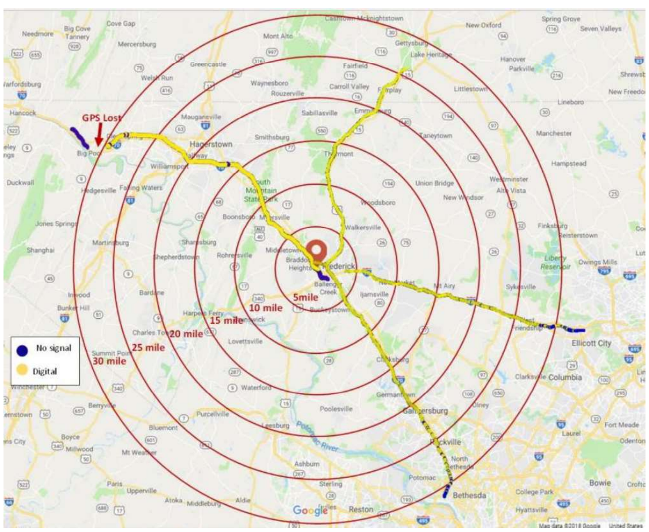



FIGURE 13: WWFD DAYTIME DRIVE TESTS (INITIAL RESULTS).

It should be noted that WWFD has a deep nighttime null, which adversely affects the MA3 waveform directly on this axis. Drive testing shows that reception is lost on this axis before the predicted contour, due to the directional antenna system suppressing the center of the channel more than the sidebands. This is likely to be a common condition in arrays with high degrees of carrier suppression, and is not evident once off a null axis.

## FUTURE WORK

Both the BE AM-6A and the Gates Five still exhibit deficiencies that currently prevent the full benefits of MA3 transmission from being demonstrated at WWFD: the AM-6A appears to reduce the crest factor of the waveform to the point that MA3 secondary and tertiary carriers are not reliable, and the Gates Five VSWR protection circuitry appears to prevent MA3 operation at full power into the antenna system. Resolving these issues in coordination with the respective manufacturers are high priorities. If either transmitter issue cannot be resolved, attention will turn to other transmitters, including an abandoned Harris DX-10, which was originally installed for a diplexed station at the WWFD transmitter site. The Harris DX-10 transmitter has already demonstrated its ability to transmit the full MA3 mode without difficulty at higher powers than for which WWFD is licensed.

Power measurement with the MA3 mode is a topic that needs to be explored more thoroughly. Spectrum analyzer and power meter measurement methods need to be compared, but both methods may be too large of a financial investment for some AM broadcasters. Standard rectifier RF current meters do not read correctly in the MA3 mode, although perhaps such hardware could be modified or an appropriate correction factor applied. Thermocouple RF current meters, the production of which has largely been discontinued for AM broadcast applications, may be examined for accuracy as a possible simple and inexpensive method to measure root mean square (RMS) currents in the MA3 mode.

A test plan for WWFD is being developed in coordination with Xperi Corporation and PILOT. A report generated from such a test plan would fulfill the requirements of WWFD's experimental authority, and contribute to the body of knowledge of "real-world" MA3 implementation. Such testing may include the documentation of noise vs. signal robustness and its effect on useful coverage area. Noise sources from power lines, electrical storms, and various indoor environments may be examined. It is hoped that such a report, along with the experience of using models of transmitters already in use at many broadcast facilities, will further the adoption of MA3 as a licensed mode of AM broadcast transmission in the United States, and demonstrate to other stations the advantages of all-digital AM broadcasting.


## ACKNOWLEDGEMENTS

The authors wish to thank the following individuals for their support and guidance: Tom King, Joshua King, and Jim Moser (Kintronic Labs), Terry Cockerill (GatesAir), Jerry Westberg (Broadcast Electronics), Phil Schmid (Nautel), Gary Cavell (Cavell, Mertz & Associates), Russ Mundschenk (Xperi Corporation), and David Layer (National Association of Broadcasters).

## REFERENCES


[1] iBiquity Digital Corporation, "HD Radio Air Interface Design Description Layer 1 AM," *SY_IDD_1012s*, Rev. G, December 14th, 2016, pp. 15-16

[2] Layton, J, *Directional Broadcast Antennas: A Guide To Adjustment, Measurement, & Testing*, 1974, pp. 127-128

[3] Layton, J, *Directional Antennas Made Simple: The "How-To" Book*, 1996, pp. 120-129

[4] Walker, B.A., "Transmission Challenges And Solutions For All-Digital AM IBOC," *NAB Broadcast Engineering Conference*, April 2014, pp. 3-4

[5] Layer, D.H., Lane, A., Mundschenk, R., Walden, E.G., Wallace, D. et al, "WBCN All-digital AM IBOC Field Test Project," *NAB Broadcast Engineering Conference*, April 2013, pp. 4-6